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COAL LIQUEFACTION: TECHNOLOGY, IMPACTS, AND TECHNICAL SUITABILITY FOR MONTANA

A Report to

The Montana Energy Advisory Council

Helena, Montana

By

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September 1976

Research Supported by the Federal Energy Administration

Cooperative Agreement Number CA-05-60763-00

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PREFACE

This report reviews the technology of coal liquefaction and its associated impacts. It relies almost solely on secondary sources and is by no means all encompassing. It is an attempt, however, to begin to bring together existing sources related to the technology of coal liquefaction. Coal liquefaction is a rapidly expanding research area, but also an area plagued by numerous uncertainties. As a result, literature only a year or two old may be outdated and essentially useless. For this reason, the report relies heavily on a few very recent reports and review articles, although the older literature was reviewed particularly for process descriptions. Of particular utility were reports prepared by the Stanford Research Institute, the Radian Corporation, and Tetra Tech, Inc., cited in the Bibliography of this report. The general schematics used to illustrate the major categories of coal liquefaction in the text are from Cochran's recent review article in Scientific American and Energy From Coal, prepared by Tetra Tech Inc., also cited in the bibliography.

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1. INTRODUCTION

Contained within the boundaries of the State of Montana are vast quantities of coal. Much of this coal, which can be characterized as subbituminous or lignite with a heating value of 6500-9000 BTU's per pound, formed as vegetation in swamps bordering shallow seas died and decomposed during early paleocene times some 65 million years ago. Most of this coal is located in southeastern Montana and over 40 billion tons of this coal is now close to the surface and can be economically strip mined. Montana coal has a gross chemical composition of carbon, hydrogen, oxygen, nitrogen, sulfur and inorganic constituents which are generally ash forming. Hydrogen and oxygen are present both chemically combined in the coal molecules and as water. A simple chemical formula for subbituminous coal would be:

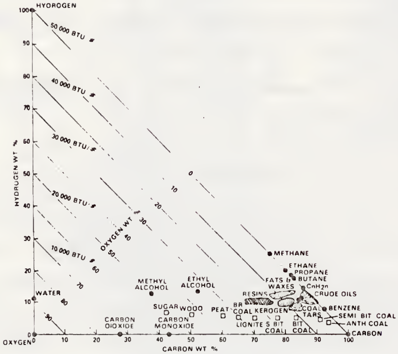
$$CH_{0.9}O_{0.2}S_{0.004}N_{0.01} + \text{Ash} + \text{Moisture}.$$

Coal is thus a primary hydrocarbon resource. While the United States' reserves of gaseous and liquid hydrocarbons are rapidly diminishing, it has enormous reserves of coal which have not been exploited. Unfortunately coal is a solid, rather than a liquid or gas. It can be highly polluting when combusted directly, and the environmental impacts of its mining are not insignificant.

Coal's solid state and its polluting characteristics can be modified by appropriate chemical reactions. For instance, the conversion of coal to liquid petroleum products requires essentially two different chemical changes: the addition of hydrogen, and the removal of oxygen.[1] Figure 1 shows the carbon, oxygen, and hydrogen ratios of a number of common hydrocarbon fuels while Figure 2 gives the minimum quantity of hydrogen required to upgrade coal to various other hydrocarbons.

FIGURE 1

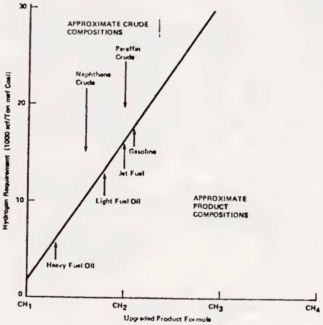
C-H-O CONTENT OF FOSSIL FUELS



Source: Mills, G. A. New Liquid Fuels from Coal: Progress in the ERDA Program. Paper presented to the Gulf Coast Lignite Conference, Austin, Texas, June, 1976.

FIGURE 2

MINIMUM HYDROGEN REQUIREMENTS FOR COAL LIQUEFACTION



SOURCE: Tetra Tech, Inc. 1975 Energy Fact Book, Arlington, VA, June, 1975.

Because of the scarcity of other hydrocarbon resources, some coal will undoubtedly be converted to other hydrocarbon forms in the future. In fact, coal could conceivably be gasified or liquefied to help relieve Montana's expected short term fuel supply imbalance due to the potential elimination of Canadian imports of oil and natural gas. The remainder of this report deals specifically with the technology for coal liquefaction, its current state of the art, economics, and potential environmental impacts. The suitability of Montana coal to liquefaction with emphasis on the possibility of supplying Montana's existing oil refineries with synthetic crude oil made from coal is also briefly reviewed.

2. COAL LIQUEFACTION TECHNOLOGY

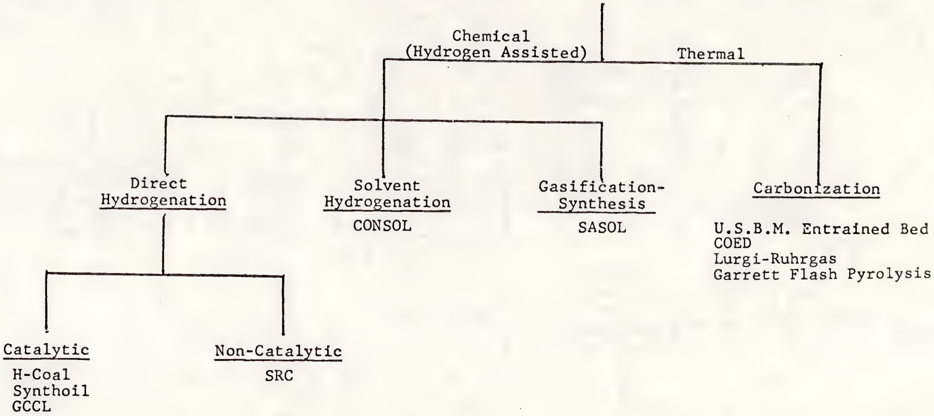
The general technology of coal liquefaction is not new. The technology for liquefying coal using several different techniques was developed in Germany in the 1920's. By 1943, during the height of the Second World War, Germany was producing up to 100,000 barrels per day (BPD) of synthetic gasoline and diesel fuel.[2] Unfortunately, the technology used by the Germans was based on a wartime environment and a totalitarian state and is both uneconomical and inefficient in today's energy market. Immediately after World War II, several bench scale and pilot plant studies of processes for coal liquefaction were undertaken in the United States; however, the economic inducement to expand and improve the existing technology was lacking, primarily because of the widespread availability of cheap crude oil and natural gas. With a few exceptions, the technology of coal liquefaction was an area of only limited research interest until the late 1960's and early 1970's when it became apparent that the United States and world reserves of petroleum and natural gas were not inexhaustible and that the United States' access to world energy supplies was not guaranteed.

Coal liquefaction is a process which produces synthetic hydrocarbon liquids from coal. As noted in the Introduction, it involves both the relative increase of hydrogen and the decrease of carbon in the constituent coal molecules. The molecular components of coal are generally aromatic ring structures with an atomic carbon to hydrogen ratio of about 0.9. The carbon to hydrogen weight ratio, however, is between 11 and 15. Liquid hydrocarbons generally have carbon to hydrogen weight ratios in the range of 6 to 8 and are molecularly less complex.[3] In order to reduce the carbon to hydrogen weight ratio and produce liquid hydrocarbons from coal, either carbon must be removed from the coal molecules or hydrogen added. Carbon can be removed from the coal molecule by carbonization (coking) or pyrolysis. Hydrogen can be added either directly or from a hydrogen donor solvent. The source of the hydrogen or the hydrogen donor solvent is usually coal itself. Coal can also be completely gasified to carbon monoxide and hydrogen and this synthesis gas can be catalytically reformed to produce a wide range of liquid hydrocarbon fuels including methanol. Coal liquefaction schemes are thus classified on the basis of whether carbon is removed or hydrogen added to the system and on how the hydrogen is added. Figure 3 shows a basic classification scheme for coal liquefaction processes. Some acronyms for the various processes and manufacturers are also included.

Although Figure 3 indicates that there are four general processes for coal liquefaction, there is still much common technology among the various processes. Figure 4 indicates the general processing steps in coal liquefaction. The various processes differ primarily in the reaction and solid separation step. All of the processes require coal preparation including drying and grinding or pulverization. All of the processes also produce both gaseous and liquid products and a solid residue which must be separated. The sulfur contained in the coal will be present in both the gaseous and liquid product streams. In every technology, acid gases (CO_2, H_2S, COS) must be removed from the system and treated to recover elemental sulfur and eliminate potential atmospheric pollutants. In every technology, the liquid products must also be separated and desulfurization of some of the liquid product streams may be required. Hydrocracking (reaction with hydrogen at elevated temperatures and pressures) would normally be the process used for the desulfurization of the liquid products. All of the technologies will also require large scale coal mining and transportation and the treatment and disposal of solid, liquid and gaseous effluent streams.[4]

FIGURE 3

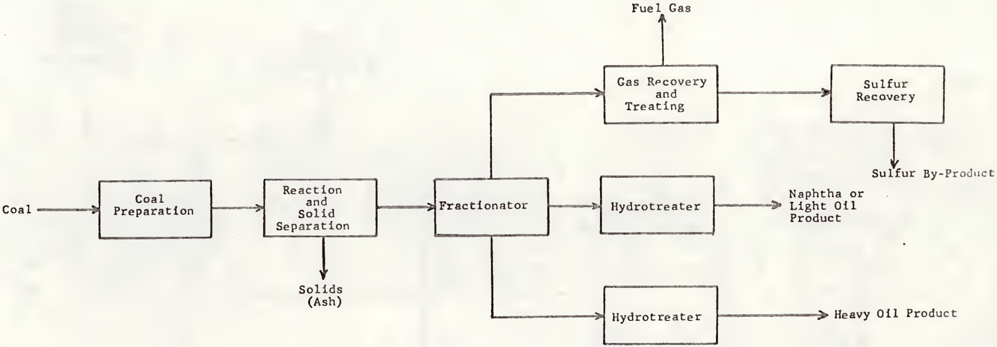
CLASSIFICATION OF LIQUEFACTION PROCESSES



SOURCE: Radian Corporation, A Western Regional Energy Development Study, RC#100-064, Austin, TX, August, 1975.

FIGURE 4

GENERAL PROCESSING STEPS IN COAL LIQUEFACTION



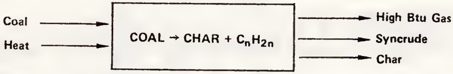
SOURCE: Radian Corporation, A Western Regional Energy Development Study, RC#100-064, Austin, TX, August, 1975.

In the subsequent sections of this report the various technologies for coal liquefaction will be explored in detail. It should be kept in mind, however, that the technologies differ primarily in the reaction process and that much technology is common to all of the processes. Research and information gaps exist in most areas of coal liquefaction technology, as will be noted later.

2.1 Coal Liquefaction by Carbonization or Pyrolysis.

Carbonization or thermal pyrolysis is a process in which the volatile components of coal are distilled by heating to high temperatures (1600°F) in the absence of air. The process yields volatile hydrocarbons, ash, and a solid carbon or char residue. The volatile hydrocarbons generally consist of a medium BTU gas and a dense synthetic liquid crude oil. The process is theoretically simple, as shown in the following schematic, and is commercially proven (coke ovens).

COAL PYROLYSIS PROCESS



Unfortunately, the pyrolysis technology used to maximize liquid and gaseous products rather than coke is plagued by a number of technical difficulties.[5] These difficulties include:

1. Residence time--The technology of coke production requires a long residence time in the reaction chamber at high temperature and batch operation. An economic process for pyrolysis based coal liquefaction will require a much shorter residence time and continuous operation.

2. Coking coals--The most readily volatized coals and thus theoretically the most amenable to pyrolysis are coking coals. Unfortunately these coals become plastic at high temperatures and coat the reactor walls, fouling the process.
3. Heat requirements--The pyrolysis process is endothermic requiring approximately 500 BTU's of heat input per pound of coal processed.
4. Thermal efficiency--The coal to oil thermal efficiency of the pyrolysis liquefaction technology is low. Yields appear to be generally on the order of 1 to 2 barrels of crude oil per ton of coal processed or approximately 25 to 50 percent.

Figure 5 shows a flow diagram for a generalized pyrolysis coal liquefaction process. There are no commercial pyrolysis coal liquefaction processes currently in existence. Following are detailed process descriptions and technical data for the existing pilot plant and bench scale coal pyrolysis processes.

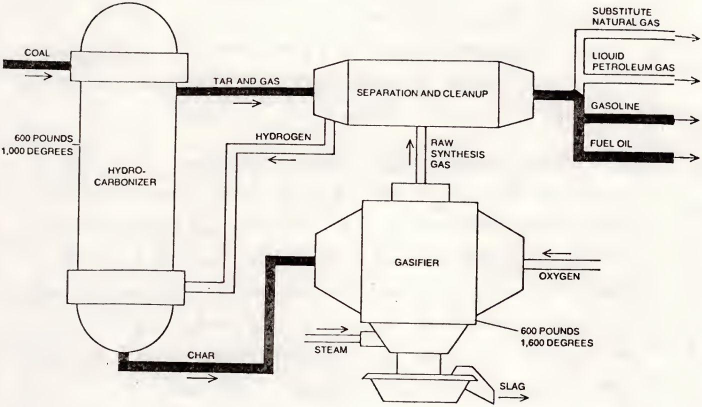
2.1.1 COED Coal Liquefaction

The Char Oil Energy Development (COED) process of coal liquefaction was developed by the FMC Corporation. The research was conducted between 1962 and 1974 under Office of Coal Research sponsorship. The U.S. Office of Coal Research (formerly in the Department of Interior) committed $20,614,000 for the development and operation of a 36-ton-per-day COED pilot plant at Princeton, New Jersey.

The COED process consists of a four-stage fluidized bed pyrolysis system. The input coal is initially preheated to 600°F with steam and combustion gases so that the softening point of the coal is increased. This pretreated coal is then routed through the four fluidized bed reactors, each sequentially operating at a higher temperature to produce gas, oil and char. The estimated recovery of input fuel as syncrude in this process is 25 to 34 percent (1.1 - 1.5 barrels/

FIGURE 5

CARBONIZATION PROCESS FOR COAL LIQUEFACTION



SOURCE: Cochran, Neal P. "Oil and Gas from Coal." Scientific American, Vol. 234, No. 5, pp. 24-29, May, 1976.

ton). A flow diagram is shown in Figure 6 along with operating conditions and a description of the products from a typical COED process.

2.1.2 Seacoke Process

The Seacoke process was developed by the Atlantic Richfield Company between 1964 and 1970. The bench scale research was sponsored by the Office of Coal Research and almost $1 million were committed to the project. Research on the Seacoke process has now ceased.

The Seacoke process also utilizes a series of fluidized bed reactors and as can be seen in Figure 7 is quite similar to the COED process. In fact the COED process has essentially replaced the Seacoke process.

2.1.3 United States Bureau of Mines Entrained Bed Process

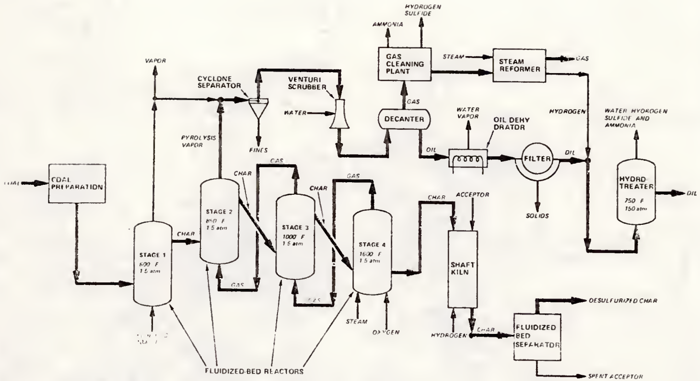
Coal is injected into a reactor with air at high velocity in the U.S. Bureau of Mines Entrained Bed process. The process requires only a short residence time for the input coal in the reaction chamber. Unfortunately, because of the air injection the gaseous hydrocarbons produced in this process are diluted with nitrogen and are not of pipeline quality. The total liquid hydrocarbon yield per ton of input coal for this process is 250 to 400 pounds. A simple schematic of the U.S.B.M. process is shown in Figure 8.

2.1.4 Lurgi-Ruhrgas Process

Coal and recycled hot char are mixed in the reaction chamber of the Lurgi Ruhrgas process. The hot char supplies process heat for the reaction. The residence time of the coal in the reaction chamber is only a few seconds, thus the liquid yields are relatively high (450-570 lbs./ton coal). A simple schematic of the process is shown in Figure 9.

FIGURE 6

COED PYROLYSIS PROCESS



Operating Conditions (4 stages):

(Operating pressure approximately 1.4 atmospheres)

Stage	**Temperature, deg F**
Preheater (dryer)	**375**
1	**600**
2	**850**
3	**1000**
4	**1600**

Recovery of input fuel as syncrude:
25-34% estimated (1.1-1.5 bbl/ton)

Products from typical COED process:

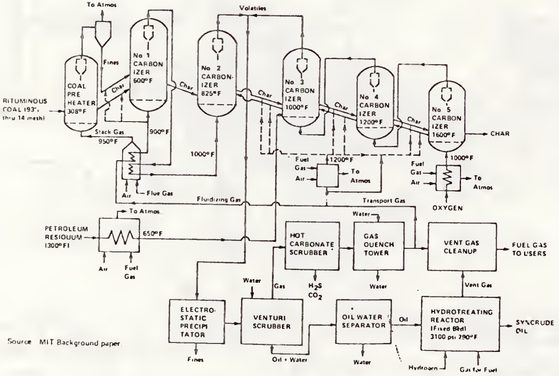
Deg API = 22; Pour point = 40 deg F;
Viscosity = 44 SSU at 100 deg F

ASTM Distillation (C_6+), deg F	
IBP	168
5%	280
10%	324
30%	489
50%	573
70%	676
90%	839
EP	871

SOURCE: Tetra Tech, Inc. 1975 Energy Fact Book, Arlington, VA, June, 1975.
U.S. Energy Research and Development Administration. Coal Liquefaction, Office of Fossil Energy, Energy Research and Development Administration, Quarterly Report, July-September 1975, ERDA 76-33-2. Washington, D.C.: 1976.

FIGURE 7

SEACOKE PROCESS



Source MIT Background paper

SOURCE: Tetra Tech, Inc. 1975 Energy Fact Book, Arlington, VA, June, 1975.

FIGURE 8

U.S.B.M. ENTRAINED BED PROCESS

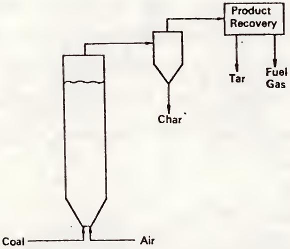
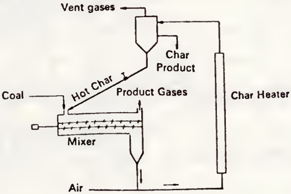


FIGURE 9

LURGI-RUHRGAS CARBONIZATION PROCESS



SOURCE: Radian Corporation, A Western Regional Energy Development Study, RC#100-064, Austin, TX, August, 1975.

2.1.5 TOSCOAL Process

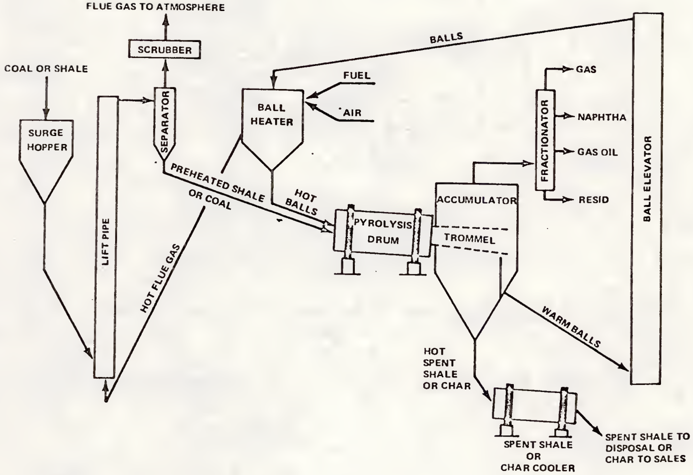
The TOSCOAL pyrolysis process is a modification of the TOSCO II oil shale retorting process. In the TOSCOAL process coal is mixed with ceramic balls heated to 800-1000°F in a rotating drum operating at atmospheric pressure. Research on this process has been carried out at the TOSCO II oil shale facility at Golden, Colorado. Figure 10 shows a flowsheet for the TOSCOAL process and an analysis of the hydrocarbon products recovered at two different operating temparatures.

2.1.6 Garrett Flash Pyrolysis

Garrett Research and Development Company, a subsidiary of Occidental Petroleum, is developing a pyrolysis liquefaction process at a pilot plant at LaVerne, California. The process uses an entrained bed reactor and operates at 1100°F. As in the Lurgi-Ruhrgas system, hot recycled char maintains the reaction temperature. The reaction products of the process are passed through a cyclone to remove the solid char. The effluent gas is then cooled to separate a liquid tar. The remaining gaseous product is used to entrain the reacting coal and to produce hydrogen for hydrotreating the liquid tar to produce synthetic crude oil. Any excess gaseous product is of fuel quality and can be sold. According to the Radian Corporation, the process can yield up to 2 barrels of synthetic crude oil per ton of input coal for a maximum thermal efficiency of 50 percent.[6] A flow diagram for the process and process yield data are shown in Figure 11.

FIGURE 10

TOSCOAL PROCESS



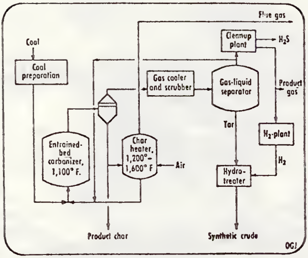
Products Recovered:

Product/ton	800 deg F	970 deg F
Gas, MSCF	0.438	1.625
Oil, bbl (16,000 Btu/lb)	0.25	0.52
Char, lbs (13,000 Btu/lb)	1100	970

SOURCE: Tetra Tech, Inc. 1975 Energy Fact Book, Arlington, VA, June, 1975.

FIGURE 11

GARRETT COAL PYROLYSIS



PRODUCTS FROM GARRETT FLASH PYROLYSIS

(BO-117)

Typical products. Pyrolysis of a West Kentucky coal produces:

Products	Wt. %	Characteristics
Char	56.7	12,100 Btu/lb
Tar	35.0	About 80% C, 7% H_2, 1.5% N_2, 10% O_2, 1.5% S
Gas	6.6	700 Btu/scf
Water	1.7	
Total	100.0	

SOURCE: Radian Corporation, A Western Regional Energy Development Study, RC#100-064, Austin, TX, August, 1975.

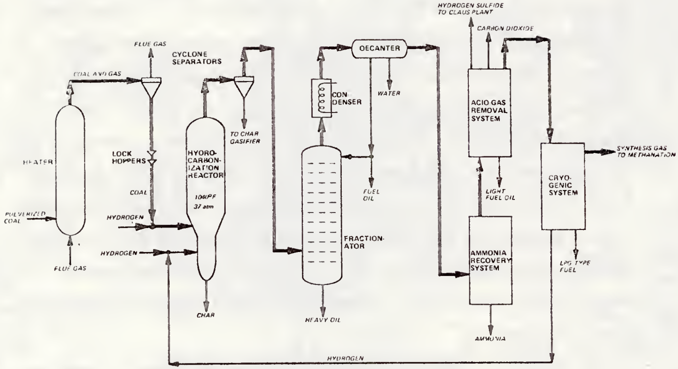
2.1.7 Hydrocarbonization Process

The Coalcon Company (a consortium including Union Carbide, Reynolds Metals, The Chemical Construction Company, I.E. Dupont, Ashland Oil, Mobil Oil, Sun Oil, and Atlantic Richfield among others) has developed a process where coal is pyrolyzed under hydrogenation conditions. The design is apparently adapted from a process developed in the late 1950's by Union Carbide. A unique phase of this process is a preoxidation step in which coal is reacted with 3 percent oxygen by weight at 660°F for several minutes to prevent agglomeration of the input coal.[7] The preoxidized coal is then heated (distructively distilled) to about 1000°F in the presence of hydrogen at a pressure of 600 pounds per square inch. The reaction products are then separated into solid and gaseous phases. The solid char from the process is gasified to produce hydrogen for the liquefaction reaction or synthetic natural gas, or burned to produce process heat. The gas phase is cooled to condense liquid hydrocarbons from the combustable gas stream. The process thus yields products ranging from pipeline quality synthetic natural gas to a low sulfur fuel oil. Liquid hydrocarbon product yields seem to be in the range of 1.5 barrels per ton of input coal. A schematic for the hydrocarbonization process is shown in Figure 12.

In January of 1975 the Coalcon Company was awarded a contract from the U.S. Energy Research and Development Administration (ERDA) for the phased design, construction, and operation of a 2600 ton per day (1/5 commercial scale) demonstration plant located in Illinois.[9] The plant would produce 3900 barrels per day of "boiler fuel" designed principally for electric utility use, and 22 million cubic feet per day of pipeline quality synthetic natural gas. The plant is scheduled to be operational in fiscal year 1980. Under the funding schedule for the project, the Federal Government has the responsibility of totally funding the preliminary engineering and the

FIGURE 12

HYDROCARBONIZATION PROCESS



SOURCE: U.S. Energy Research and Development Administration. Coal Demonstration Plants, Office of Fossil Energy, Energy Research and Development Administration, Quarterly Report, July-September 1975, ERDA76-32-3. Washington, D.C.: 1976.

demonstration plant engineering. The engineering design for the project is due to be evaluated in the fall of 1976. Under the original agreement the demonstration plant construction, operation, and evaluation costs were to be shared equally by government and industry. The total value of the original contract is $237,222,300 with the U.S. Government share being $129,836,150. This design is essentially complete; however, Hammond reports that costs for the plant have risen considerably, and ERDA has postponed any final decision on the project until 1977.

2.1.8 Flash Hydropyrolysis

A final pyrolysis liquefaction process currently in the bench scale research phase is flash hydropyrolysis. In flash hydropyrolysis coal is converted directly to liquid and gaseous hydrocarbons by very rapid heating (a few seconds) with preheated hydrogren followed by a similar rapid cooling. The percentage of liquids appearing in the reaction products from this process is enhanced and the conversion to liquids can be further increased by the use of catalysts. Under laboratory conditions, flash hydropyrolysis using an ammonium molybdate catalyst produced reaction products with essentially no solid char. Research on flash hydropyrolysis under ERDA sponsorship is being conducted at the Brookhaven National Laboratory, the City University of New York Clean Fuels Institute, and the Institute of Gas Technology. A schematic diagram of the flash hydropyrolysis reactor and the yield structure of the reaction products from the City University of New York research is shown in Figure 13.

2.1.9 Cities Service Co. Hydropyrolysis Process

The Cities Service Co. hydropyrolysis process non-catalytically hydrogenates dry coal in a single step to produce both liquid hydrocarbons and

FIGURE 13

FLASH HYDROPYROLYSIS

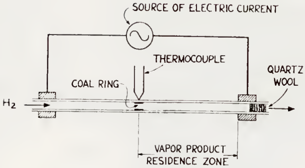


Fig. 1. Schematic diagram of the reactor. The location of the coal deposit in the tube and the hydrogen flow rate are selected to give the desired vapor product residence time.

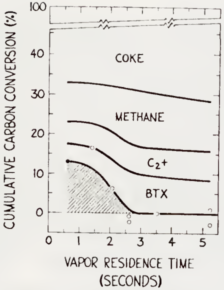


Fig 2. Yield structure from the flash hydrogenation of Illinois No. 6 coal at 100 atm and about 700°C as a function of the vapor product residence time; C_{2+}, yield of ethane and propane (with a trace of butane). The shaded area in the lower left is carbon unaccounted for by the carbon balance. A plotted point is the carbon not found in the vapor products of hydrogenation or carbon oxides from a subsequent combustion; a point falling on the abscissa represents a perfect carbon balance.

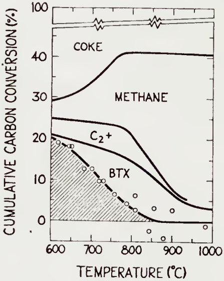


Fig. 3. Yield structure at a product residence time nominally 0.6 second as a function of temperature. (For an explanation of the symbols, shaded area, and plotted points, see the legend for Fig. 2). The propane yield falls linearly from 2 percent at 620°C to nearly zero at 780°C. The ratio of benzene to total BTX rises nearly linearly from 0.41 at 620°C to substantially unity beyond 790°C.

SOURCE: Squires, Arthur M., et al. "Flash Hydrogenation of a Bituminous Coal," Science, Volume 189, 5 September 1975, pp. 793-795.

pipeline quality gas (primarily methane). The process has been under development for approximately two years using a 2 lb per hour bench scale design. Plans are now underway to develop a larger unit. Research to date has shown that the process does not produce high boiling tars; however, a char is produced which can be gasified to produce hydrogen or synthetic natural gas.

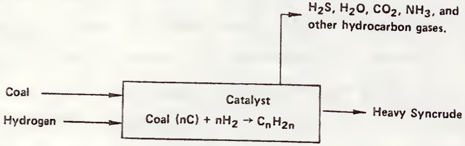
In the process, dry pulverized coal is fed in batches to a hopper where it is pressurized to reactor conditions with hydrogen. Coal enters the top of the reaction chamber through a star wheel feeder and standpipe where it contacts more preheated hydrogen. The coal is devolatilized as it falls through the reaction chamber into a char pot. The volatile components are passed through three sequential heat exchangers to separate the gaseous and liquid products and recycle hydrogen. Residence time in the reaction chamber varies from 100 to 300 milliseconds at temperatures at or above 1200°F.

North Dakota lignite and Kentucky bituminous coals have been processed with carbon yields of up to 80 percent. Light liquid yields have been up to 16 percent by weight. These liquid products are primarily benzene (94%) with some naphthalene and anthracene. These products can be sold as is without further hydrotreating.

2.2 Coal Liquefaction by Direct Hydrogenation

Coal is liquefied in the direct hydrogenation process through a reaction with hydrogen at high pressure, often in the presence of a catalyst. The general process scheme requires coal to be pulverized, slurried with a recycled hydrocarbon solvent from the process, reacted with hydrogen at high temperature and pressure, and the reaction products removed from the system. In the reaction, the organic fraction of the coal is dissolved; however, the reaction is usually not complete leaving some unreacted coal in the system along with a solid inorganic ash. Following the hydrogenation reaction, the liquid phase is decompressed and distilled. A theoretical schematic diagram of the direct hydrogenation process is shown below and a generalized flow chart for the process is given in Figure 14.

DIRECT HYDROGENATION PROCESS


H_2S, H_2O, CO_2, NH_3, and other hydrocarbon gases.
Coal
Hydrogen
Catalyst
Coal (nC) + $nH_2 \rightarrow C_nH_{2n}$
Heavy Syncrude

The direct hydrogenation process appears to be a promising technology for coal liquefaction. It produces a high liquid product yield (3 barrels of liquid product per ton of input coal) and has a thermal efficiency of up to 75 percent. Currently there are at least five different direct hydrogenation processes in existence. A description of each of the individual processes follows.

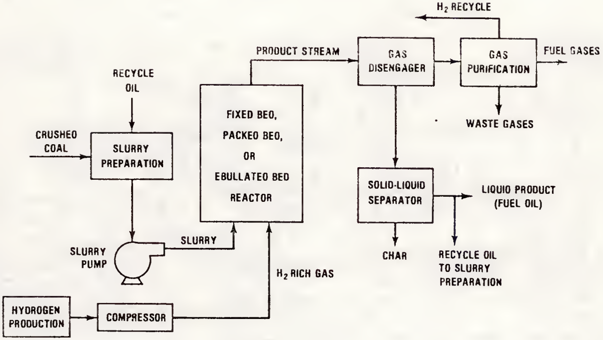
2.2.1. German Hydrogenation Processes

The development of the German direct hydrogenation coal liquefaction process was initiated by Bergius in 1911 and development continued through the 1920's. The first commercial direct hydrogenation liquefaction plant developed by I. G. Farben began operation in 1927. Seven plants were in existence by 1939 and during World War II German synthetic fuel production by direct hydrogenation rose to over 64,000 barrels per day.[10]

In the German direct hydrogenation process pulverized coal and hydrogen were reacted at variable pressures and temperatures in the presence of a catalyst to produce a synthetic crude oil. By varying temperature, pressure, catalysts, and the coal to hydrogen ratio products ranging from hydrocarbon gases, through aviation fuel, to a very heavy fuel oil could be produced. Figure 15 shows a schematic diagram of the German direct hydrogenation process while Figure 16 gives typical operating conditions and product yield information.

FIGURE 14

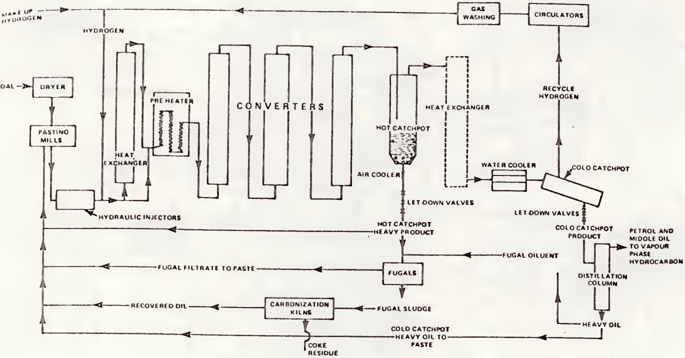
DIRECT HYDROGENATION PROCESS FOR COAL LIQUEFACTION



SOURCE: U.S. Energy Research and Development Administration. Energy from Coal, Prepared for Office of Fossil Energy, United States Energy Research and Development Administration under Contract No. E(49-18)-2225 by Tetra Tech, Inc., ERDA 76-67. Washington, D.C.: Government Printing Office, 1976.

FIGURE 15

GENERAL SCHEME OF GERMAN DIRECT HYDROGENATION



SOURCE: Tetra Tech, Inc. 1975 Energy Fact Book, Arlington, VA, June, 1975.

FIGURE 16

PRODUCT YIELD AND OPERATING CONDITIONS

GERMAN DIRECT HYDROGENATION

Plant	Wt% gasoline and middle oil
Leuna (1922) (Brown coal)	50
Scholven (Bituminous)	60-61
Gelsenberg (Bituminous)	67
Stettin-Politz (Bituminous)	57-59

Plant	Nominal Capacity*, te/yr (bbl/day)	Maximum Output, te/yr (bbl/day)
Leuna	620,000 (12,300)	640,000 (12,700)
Scholven	220,000 (4,300)	240,000 (4,700)
Gelsenberg	400,000 (7,900)	435,000 (8,600)
Stellin-Politz	700,000 (12,800)	750,000 (14,800)
Wesseling	200,000 (3,900)	230,000 (4,500)
Blech hammer	425,000 (8,400)	65,000 (1,300)

*It should be noted that even the largest German plants would by todays standards be considered little more than a large pilot plant.

Operating Conditions:

Plant	Pressure, atm	Temperature, deg F	Catalyst
Leuna (1927) (Brown coal)	230	806-914	Crude iron oxide
Scholven (Bituminous)	300	860	Tin oxalate—ammonium chloride
Gelsenberg and Stellin-Politz (Bituminous)	700	896	$FeSO_4 \cdot H_2O$, crude iron oxide, and sodium sulphide

SOURCE: Tetra Tech, Inc. 1975 Energy Fact Book, Arlington, VA, June, 1975.

2.2.2 H-Coal Process

The H-Coal process development was a joint undertaking of Hydrocarbon Research, Inc., and the U.S. Office of Coal Research. An ebullated bed reactor is the central feature of the H-Coal process where ground coal and hydrogen are reacted in the presence of a cobalt molybdate catalyst. The H-Coal ebullated bed reactor is shown in Figure 17. Input slurried coal and hydrogen enter the bottom of the reactor. The process coal is ground finer than the catalyst allowing unreacted coal to be removed at the top of the reactor along with the liquid product. The reactor operates at 800-900°F and 1500-3000 psi pressure. A schematic of the entire H-Coal process for a 1044 tons per day plant is shown in Figure 18. Product yields are given in Figure 19. Liquid product yields from the H-Coal process have been reported to be as high as 4.3 barrels per ton of input coal.[11] The overall thermal efficiency of the process is estimated to be approximately 70 percent.

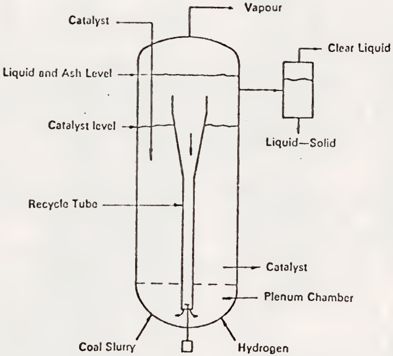
Work on the H-Coal process began in 1965. The Office of Coal Research terminated support for the project in 1968 at which time approximately $2 million had been spent in process development. Industry support for the H-Coal process continued after 1968. Initial process development work was carried out at a 3 ton per day pilot plant at Trenton, New Jersey. ERDA is now considering plans for the construction of a 300-600 tons per day H-Coal pilot plant to be located at Cattletsburg, Kentucky.[12]

2.2.3 Synthoil Process

The Synthoil process is being developed by the U.S. Bureau of Mines. In the Synthoil process, a slurry of pulverized coal and recycle solvent is mixed with hydrogen, preheated and routed to a fixed bed reactor. Reactor conditions are 840°F, 2000-4000 psi pressure, and a cobalt molybdate catalyst. The liquid yield from the Synthoil process is approximately 3 barrels per ton of input coal. Figure 20 shows a schematic of the Synthoil process.

FIGURE 17

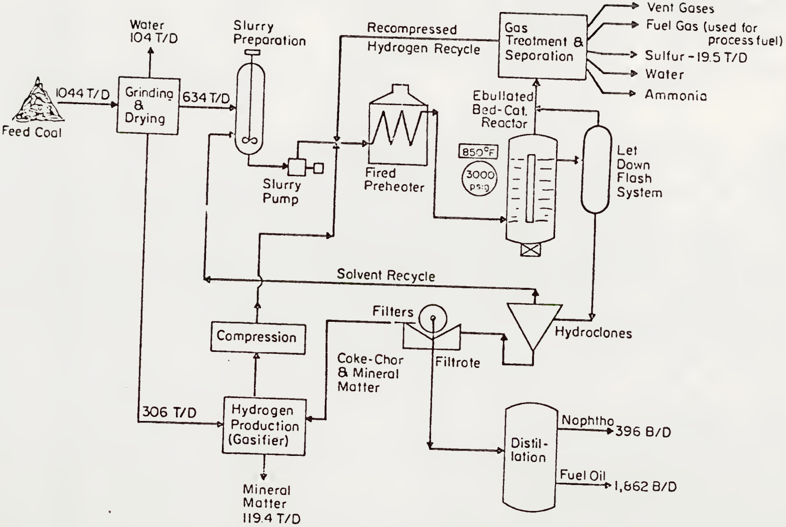
H-COAL EBULLATED BED REACTOR



SOURCE: Radian Corporation, A Western Regional Energy Development Study, RC#100-064, Austin, TX, August, 1975.

FIGURE 18

H-COAL PROCESS FLOW CHART



SOURCE: Radian Corporation, A Western Regional Energy Development Study, RC#100-064, Austin, TX, August, 1975.

FIGURE 19

H-COAL PROCESS YIELDS

(Based on Moisture and Ash Free Coal)

Illinois No. 6 bituminous coal

	Yields, % by weight
Light gas, C_1-C_3	10.2
Liquid product	71.0
Unconverted char	10.7
Hydrogen sulfide, water, ammonia	14.0

$$\text{Conversion} = \frac{\text{maf coal-char}}{\text{maf coal}}\,(100) = 89.3\ \%\ \text{by weight}$$

Liquid product inspections

ASTM cut points	% by volume	Degrees, API	Liquid yield % by weight of moisture and ash free coal	Liquid yield barrels per ton of moisture and ash free coal	Nitrogen, p.p.m.	Sulfur, p.p.m.
C_4 to 400°F.	31.6	49.2	18.5	1.35	1,000	990
400° to 680°F.	39.7	21.1	27.5	1.70	1,700	1,600
680° to 975°F.	15.8	0.3	12.7	0.67	4,100	1,000
975°F.+	12.9	−20	12.3	0.55		
Total	100.0		71.0	4.27		

Wyoming subbituminous coal

	Yields, % by weight
Light gas, C_1-C_3	10.8
Liquid product	56.1
Unconverted char	18.6
Hydrogen sulfide, water, ammonia	12.9
Carbon monoxide and carbon dioxide	6.6

Conversion = 81.4 % by weight

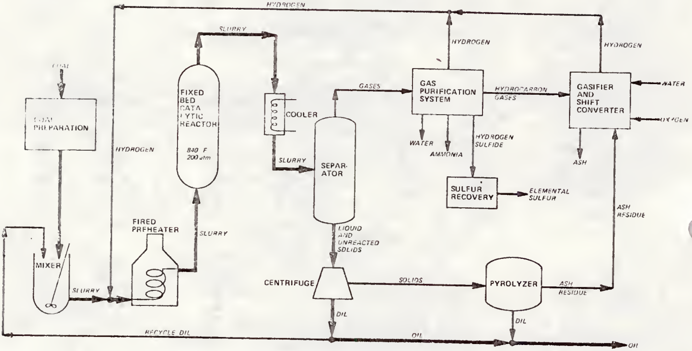
Liquid product inspections

ASTM cut points	% by volume	Degrees, API	Liquid yield % by weight of moisture and ash free coal	Liquid yield barrels per ton of moisture and ash free coal	Nitrogen, p.p.m.	Sulfur, p.p.m.
C_4 to 400°F.	39.4	50	18.5	1.35	2,000	<700
400° to 650°F.	27.6	21	15.5	0.95	3,000	<700
650° to 975°F.	18.0	4	11.1	0.62	6,000	<700
975°F.+	15.0	−16	11.0	0.52		
Total	100.0		56.1	3.44		

SOURCE: Radian Corporation, A Western Regional Energy Development Study, RC#100-064, Austin, TX, August, 1975.

FIGURE 20

U. S. BUREAU OF MINES SYNTHOIL PROCESS



SOURCE: U. S. Energy Research and Development Administration. Coal Liquefaction, Office of Fossil Energy, Energy Research and Development Administration, Quarterly Report, July-September 1975, ERDA76-33-2. Washington, D.C.: 1976.

The development of the Synthoil process was undertaken at the U.S. Bureau of Mines Research Center at Pittsburgh, Pennsylvania, where a one-half ton per day pilot plant was constructed. The Foster-Wheeler Corporation is currently contracting with ERDA to construct a 24-barrel per day pilot Synthoil plant at Bruceton, Pennsylvania. The value of the contract is approximately $8 million.

2.2.4 Gulf Catalytic Coal Liquids (CCL) Process

Another catalytic direct hydrogenation process is currently being developed by the Gulf Research and Development Corporation. Current work has been at the bench scale, however a small pilot plant is being constructed. The process is somewhat similar to the H-Coal process as coal is pulverized, slurried with a recycle solvent, hydrogenated, preheated and routed to the reaction vessel. Operating conditions are 800 - 900°F and 3000 psi. In this process, solid separation is accomplished through the use of hydrocyclones and rotary drum filters. Product yield from the process is approximately 3 barrels per ton with 72 percent of the product being a heavy fuel oil and 28 percent equivalent to a distillate fuel. A schematic of the Gulf CCL process is shown in Figure 21.

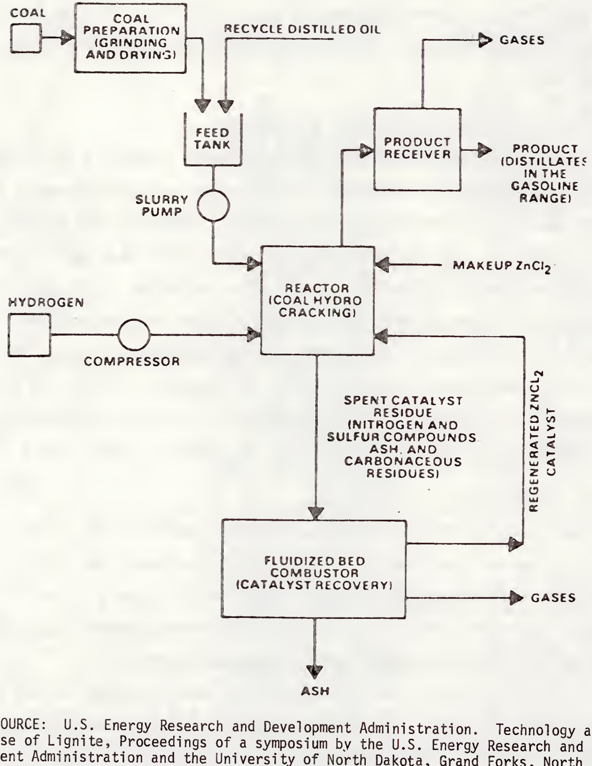
2.2.5 Zinc Chloride Catalysis Process

The zinc chloride catalysis process is being developed by the Conoco Coal Development Company under a three year, $6 million grant from the Energy Research and Development Administration. Shell Oil is a supporting participant in the project. A 2.5 lb/hr bench scale unit is in operation and a 1.2 ton per day process development unit is currently being designed.

The process requires input coal to be pulverized and slurried in recycle oil. The slurry is then fed into the reaction chamber where it encounters hydrogen and molten zinc chloride. The reactor conditions are 700-825°F and 1500-3000 psi. One step hydrocracking occurs in this molten salt reactor and

FIGURE 21

ZINC CHLORIDE CATALYST PROCESS


COAL
COAL PREPARATION (GRINDING AND DRYING)
RECYCLE DISTILLED OIL
GASES
FEED TANK
PRODUCT RECEIVER
PRODUCT (DISTILLATES IN THE GASOLINE RANGE)
SLURRY PUMP
MAKEUP ZnCl2
REACTOR (COAL HYDRO CRACKING)
HYDROGEN
COMPRESSOR
SPENT CATALYST RESIDUE (NITROGEN AND SULFUR COMPOUNDS ASH, AND CARBONACEOUS RESIDUES)
REGENERATED ZNCL2 CATALYST
FLUIDIZED BED COMBUSTOR (CATALYST RECOVERY)
GASES
ASH

SOURCE: U.S. Energy Research and Development Administration. Technology and the Use of Lignite, Proceedings of a symposium by the U.S. Energy Research and Development Administration and the University of North Dakota, Grand Forks, North Dakota, May 14-15, 1975. Grand Forks, North Dakota: 1975 the distillate product is then separated from product gases. Reaction products include fuel oil or distillate and low BTU gas.

The spent zinc chloride catalyst is regenerated with a fluidized bed combustor and recycled. Regeneration and recycle are required because of hydrolysis and other chemical reactions with the coal ash. Because of the large quantities of catalyst involved in the process, recycle is economically important.

2.2.6 Solvent Refined Coal (SRC)

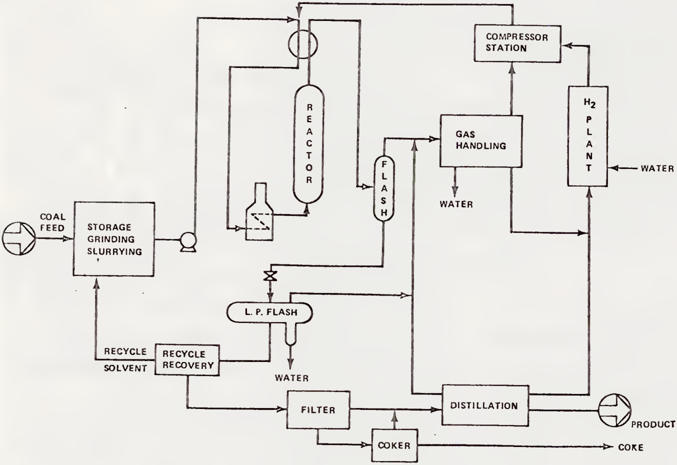
The Solvent Refined Coal process was originally developed to yield a desulfurized de-ashed solid hydrocarbon fuel designed primarily as a power plant boiler fuel. Initial work on the process was begun in 1962 by the Spencer Chemical Company which was later acquired by the Gulf Oil Corporation. Process development work was then continued by the Pittsburgh and Midway Coal Company (PAMCO) a Gulf Oil subsidiary using a 1 ton per day bench scale reactor.

As in other direct hydrogenation processes, pulverized coal is slurried with a recycled solvent. The slurry is then mixed with hydrogen, preheated and routed to the reaction vessel. The direct hydrogenation takes place at 850°F and 1050 psi pressure. The SRC process differs from other direct hydrogenation processes as no catalyst is used. The resultant product is a solid which melts at approximately 350°F and must be further hydrotreated to produce liquid hydrocarbons. Thermal efficiency for the process is approximately 62.5 percent. A schematic of the SRC process is shown in Figure 22. Product yields associated with the theoretical design of a 10,000 ton per day SRC demonstration plant are shown in Figures 23 and 24.

There are currently two SRC pilot plants in operation in the United States. The Pittsburgh and Midway Coal Company (PAMCO) is currently operating a 75 ton per day pilot plant at Tacoma, Washington. A 6 ton per day pilot plant sponsored by the Electric Power Reseach Institute and the Southern Services Company has

FIGURE 22

CONCEPTUAL FLOW DIAGRAM FOR GULF
CATALYTIC COAL LIQUIDS PROCESS



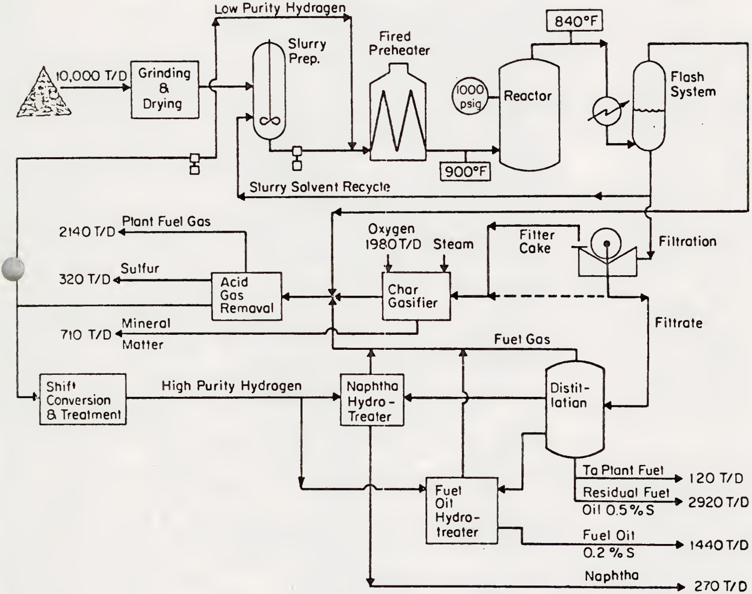
SOURCE: Tetra Tech, Inc. 1975 Energy Fact Book, Arlington, VA, June, 1975.

FIGURE 23

SCHEMATIC FLOW SHEET

Ralph M. Parson's Design for a 10,000 Ton Per Day

Solvent Refined Coal Demonstration Plant



SOURCE: Radian Corporation, A Western Regional Energy Development Study, RC#100-064, Austin, TX, August, 1975.

FIGURE 24

PROCESS YIELDS

Ralph M. Parson's Design for a 10,000 Ton Per Day
Solvent Refined Coal Demonstration Plant

1) Two primary boiler fuels:

a. Four billion BTU/hr (minimum) of liquid, with a maximum sulfur content of 0.5%

Flash point	150°F
Higher heating value	16,600 BTU/lb
° API	-9.7 60/60°F

b. Two billion BTU/hr (minimum) of hydrogenated liquid, with a maximum sulfur content of 0.2%.

Flash point	150°F
Boiling range	400 to 870°F
Higher heating value	18,330 BTU/lb
° API	13.9 60/60°F

2) Hydrogenated light oils with the following approximate characteristics:

Boiling range	C_4 - 400°F
Gravity	52°API
Nitrogen	5 ppm
Sulfur	1 ppm

SOURCE: Radian Corporation, A Western Regional Energy Development Study, RC#100-064, Austin, TX, August, 1975.

been constructed and is operating at Wilsonville, Alabama. The U.S. Office of Coal Research, now in ERDA, has supported the PAMCO research and has in total invested approximately $42 million in SRC research. In addition, the Ralph M. Parsons Company has completed under ERDA sponsorship a "demonstration plant" design for a 10,000 ton per day SRC plant which would produce approximately 25,000 barrels per day of liquid hydrocarbons.[13]

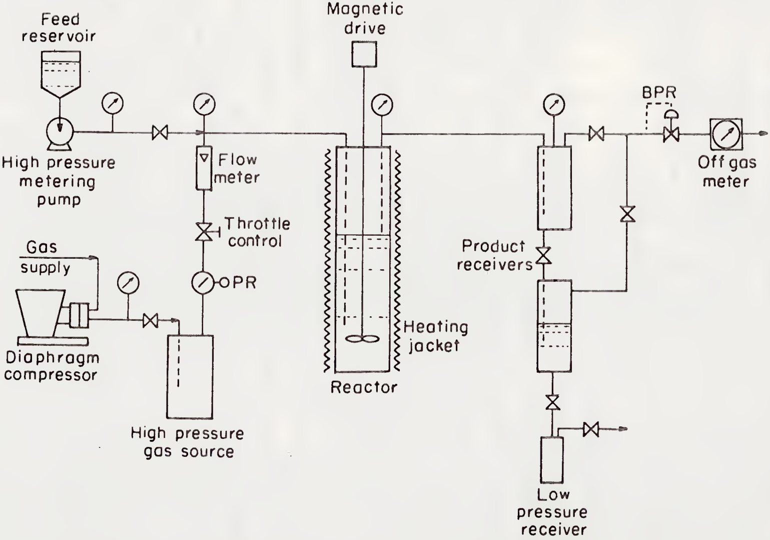
2.2.7 COSTEAM Process

The COSTEAM process is currently being developed at the ERDA Pittsburg Energy Research Center. A 1/2 ton per day process development unit is in operation at Pittsburg and a 10 ton per day plant is to be designed and constructed at the ERDA Grand Forks Energy Research Laboratory, Grand Forks, North Dakota. The process is specifically designed to utilize lignite.

In the process pulverized lignite and some of the product oil are slurried and pumped with process gas (CO and steam) into a stirred reactor. The process is catalyzed by the natural alkalinity present in the lignite ash. The catalysis promotes the CO + steam reaction to produce hydrogen which liquefies the lignite. Reactor conditions are 800°F and 4500 psi. The necessary water for the reaction is also naturally present in the lignite. Thus a separate water feed is not required. The product gases from the process are delivered to a receiver where the oil and gas ($CO + H_2$) are separated. Residual solids are removed by centrifugation. Process yields of fuel oil are approximately 70 percent by weight for the initial process development unit.

FIGURE 25

COSTEAM PROCESS

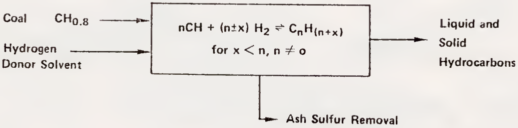


SOURCE: U.S. Energy Research and Development Administration. Technology and The Use of Lignite, Proceedings of a symposium by the U.S. Energy Research and Development Administration and the University of North Dakota. Grand Forks, North Dakota, May 14-15, 1975. Grand Forks, North Dakota: 1975.

2.3 Solvent Hydrogenation

The solvent hydrogenation liquefaction process differs from direct hydrogenation in the mechanism of hydrogenation. Hydrogen for the liquefaction process comes from a hydrogen "donor" solvent in this process. A hydrogen donor solvent is capable of transferring hydrogen to the reactant coal, hence decreasing the coal's carbon to hydrogen ratio. A coal derived hydrogen donor solvent (such as tetralin) is often used in the process. A theoretical process diagram for the solvent hydrogenation process is given below and a generalized process schematic is shown in Figure 26. There are currently two solvent hydrogenation processes being developed in the United States; a description of these processes follows.

SOLVENT HYDROGENATION

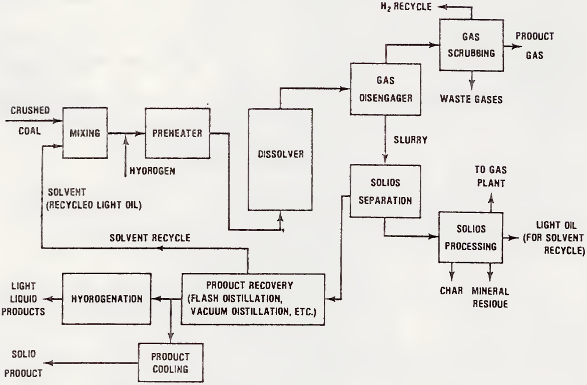

Coal $CH_{0.8}$
Hydrogen Donor Solvent
$nCH + (n \pm x) H_2 \rightleftharpoons C_nH_{(n+x)}$
for $x < n, n \neq o$
Liquid and Solid Hydrocarbons
Ash Sulfur Removal

2.3.1 Consol Synthetic Fuels Process

The Consol Synthetic Fuels process was developed between 1963 and 1970 by the Consolidation Coal Company with the support of the Office of Coal Research. Over $20 million was spent in constructing and operating a 70 ton per day pilot plant at Cresap, West Virginia. Because of persistent mechanical failures, the plant was shut down in 1970. Although the pilot plant research was not completely successful, Consol concluded that the process was technically feasible.[14] The Cresap, West Virginia pilot plant is now scheduled to be reactivated by the Flour Corporation as a general coal processing research facility where several coal to liquid hydrocarbon processes will be studied.

FIGURE 26

SOLVENT HYDROGENATION PROCESS FOR COAL LIQUEFACTION



SOURCE: U.S. Energy Research and Development Administration. Energy from Coal, Prepared for Office of Fossil Energy, United States Energy Research and Development Administration under Contract No. E(49-18)-2225 by Tetra Tech, Inc., ERDA 76-67. Washington, D.C.: Government Printing Office, 1976.

The Consol Synthetic Fuels process uses a hydrogen donor solvent to dissolve dried and ground, slurried coal. This slurry is then routed through a preheater to a stirred reaction vessel. The operating conditions of the reaction vessel are 700 - 750°F and 400 psi. After reaction, the liquid and solid phases are separated. The liquid phase is then hydrotreated to desulfurize the product and regenerate the hydrogen donor solvent. Thermal efficiency for this process has been reported to be 62 to 69 percent. A schematic of the Consol Synthetic Liquid Fuels process is shown in Figure 27 with operating conditions and product yield information given below:

Operating Conditions:

Unit	Temperature, deg F	Pressure, psi
Preheater	450	~ambient
Extractor	765	150
Hydrotractor	800	3000

Products Produced:

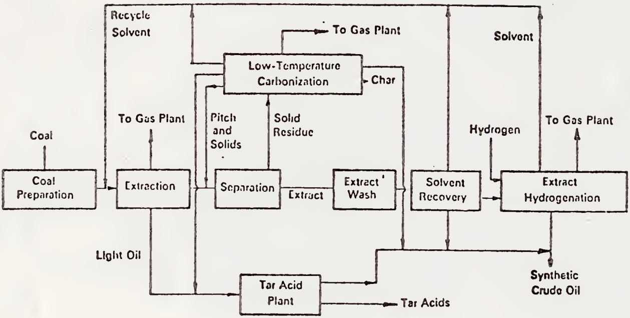
Product	Product/Ton Coal (Pittsburgh Seam)	Characteristic
Gas	3.424 MSCF	933 Btu/SCF
Naphtha	0.52 bbl	58 deg API, 5.2 MM Btu/bbl
Fuel Oil	1.52 bbl	10.3 deg API, 6.3 MM Btu/bbl
NH_3	11 lb	
Sulfur	71 lb	
Ash	213.6 lb	

2.3.2 Exxon Donor Solvent Process

The Exxon Donor Solvent process is being developed at the Exxon Research Center at Baytown, Texas. A one-half ton per day pilot plant is in operation. The process uses a hydrogenated solvent to donate hydrogen to the coal and also involves a catalyst external to the liquefaction reactor.[15] The Exxon process is proprietary and no further process details are available; however, the design of a large 200-300 ton per day pilot plant was scheduled to be completed in 1975.[16] ERDA began supporting the Exxon Donor Solvent process in July 1976, so more process details should soon be available.

FIGURE 27

CONSOL SYNTHETIC FUELS PROCESS

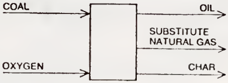


SOURCE: Radian Corporation, A Western Regional Energy Development Study, RC#100-064, Austin, TX, August, 1975.

2.4 Synthesis Gas Liquefaction

Input coal is completely gasified and catalytically reformed in the Synthesis Gas Liquefaction process. With proper choice of catalyst and operating conditions, products ranging from methanol to heavy oils and waxes can be produced. Input coal for the process can be gasified through any one of several different procedures. Synthesis Gas Liquefaction was used extensively by the Germans in World War II and although the process is expensive and inefficient, it is the only liquefaction process in commercial operation in the world today. The South African Coal, Oil, and Gas Corporation (SASOL) operates a 5400 ton per day liquefaction plant at Sasolburg, South Africa. In fact plans have recently been announced for tripling the production capacity of this plant.[17] A general schematic of the Synthesis Gas process is given below. The Synthesis Gas process for the production of both methanol and gasoline-diesel fuel products will be reviewed in the following sections.

SYNTHESIS GAS LIQUEFACTION



2.4.1 SASOL Process

The SASOL process relies on the Fischer-Tropsch synthesis for the production of liquid hydrocarbon fuels from coal. The Fischer-Tropsch synthesis was first reported in the literature in 1925. By 1939 a total of nine plants having a combined capacity of approximately 15,000 barrels per day were in operation in Germany.[18] The same process is now used to produce approximately 5000 barrels of liquid hydrocarbons per day at the SASOL plant.

The Fischer-Tropsch synthesis is actually the second stage in the liquefaction process. Coal must first be gasified and then purified to produce a synthesis gas consisting of carbon monoxide and hydrogen in a molecular ratio of 1/2. This synthesis gas is then routed to a reaction vessel where the Fischer-Tropsch reaction takes place. The Fischer-Tropsch synthesis gas reactions are:

$$nCO + 2nH_2 \rightarrow (CH_2)_n + nH_2O$$

$$2nCO + nH_2 \rightarrow (CH_2)_n + nCO_2$$

$(CH_2)_n$ is the symbolic representation of a hydrocarbon with n carbon atoms where n is larger than 4 or 5. The Fischer-Tropsch reactions occur at 600°F and 350 psi with an iron catalyst. A block flow diagram of the SASOL liquefaction process is shown in Figure 28. If the SASOL process is maximized for the production of gasoline, the thermal efficiency of the process is 40 to 45 percent.

2.4.2 Methanol Synthesis

The synthesis of methanol from coal is very similar to the Fischer-Tropsch synthesis. The only major difference is in the final process step where the nature of the catalyst and processing conditions are different. In methanol synthesis, a copper zinc catalyst is used at 500°F and 1500 psi. The Methanol Synthesis reactions are:

$$CO + 2H_2 \rightarrow CH_3OH$$

$$CO_2 + 3H_2 \rightarrow CH_3OH$$

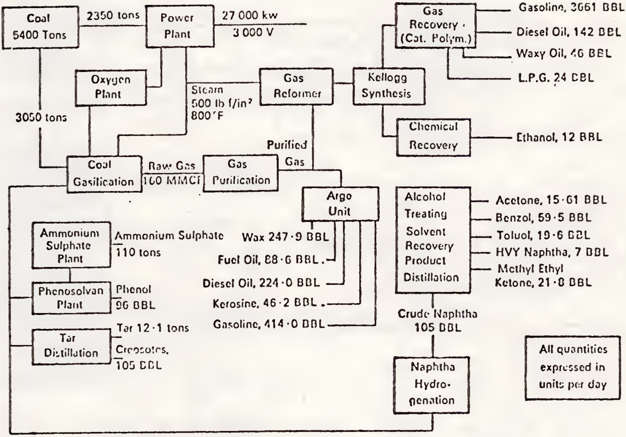
CO_2 is formed by the carbon monoxide shift conversion:

$$CO + H_2O \rightarrow CO_2 + H_2$$

The thermal efficiency for methanol conversion is 56 percent if the heating value of all byproducts are considered. The thermal efficiency for methanol alone is 40 percent. A block flow diagram for methanol synthesis is shown in Figure 29.

FIGURE 28

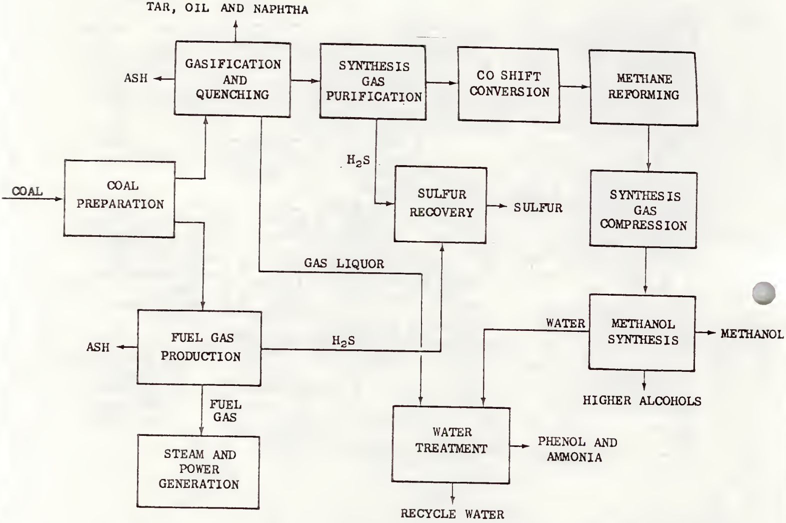
SASOL LIQUEFACTION PROCESS



SOURCE: Radian Corporation, A Western Regional Energy Development Study, RC#100-064, Austin, TX, August, 1975.

FIGURE 29

METHANOL SYNTHESIS



SOURCE: Stanford Research Institute. Impacts of Synthetic Liquid Fuel Development--Automotive Market. Draft Final Report. Menlo Park, CA: Stanford Research Institute, January, 1976.

2.5 Technological Problems and Prospects for Commercialization

The technology for coal liquefaction can only be described as a developing technology. Although the Germans produced up to 100,000 barrels per day of synthetic liquid fuels during World War II and South Africa is currently operating a 5000 barrel per day plant, the technologies used in these plants are generally considered to be inefficient, uneconomic, and inappropriate in the United States. In addition, the most common size for a coal liquefaction "module" in the United States is 100,000 barrels per day. In comparison the largest existing or historical plant could be considered only a small "demonstration" plant. Liquefaction research in the United States is focusing on both improving existing technology and developing new processes.

There are no commercial sized coal liquefaction plants in existence in the United States. In fact, the largest liquefaction pilot plant in existence processes only 75 tons of coal per day.[19] There are plans underway to build two larger coal liquefaction pilot or demonstration sized plants in the United States; however, there are a number of serious technical difficulties which must be solved before the technologies can confidently undergo very large scale-up. The Stanford Research Institute does not expect the first commercial coal liquefaction plants for at least 10 years.[20]

The Radian Corporation has identified eight general problem areas in coal liquefaction technology.[21] These areas are: (1) Thermal Efficiency; (2) Water Management; (3) Solids Separation; (4) Solvent to Coal Ratio; (5) Solvent Generation; (6) Preheat; (7) Pressure Let-Down; (8) Hydrogen Production. The first three problem areas are particularly serious.

The thermal efficiency of the currently existing coal liquefaction process ranges from 40 to ~75 percent. Most commonly, efficiencies are in the 60 percent range. Since the liquefaction process is endothermic, energy is required to "crack" the coal molecule that cannot be recovered as liquid fuel. Processes which optimize thermal efficiency should be favored for development, but the desirability of the large-scale development of an inefficient technology largely for an extremely inefficient end use (automotive transportation) is also an issue being raised.

Coal liquefaction technologies require large quantities of water (actual water requirements will be explored in section 3). Since coal liquefaction plants are likely to be located close to coal source, the concurrent availability of water must also be considered. The water availability problem for coal liquefaction is particularly serious since a great deal of available coal is located in the semi-arid and arid west. Available water adjacent to sufficient quantities of coal is nearly always in short supply in these regions and conflicts over alternative water uses will undoubtedly arise.

Solids separation is important since the presence of solids, especially incombustible solids in liquid fuels for transportation use, will result in poor operation and excessive engine wear. Solids separation was one of the major problem areas at the Consol pilot plant at Cresap, West Virginia, and was unresolved when the pilot plant shut down.

The other problem areas noted by Radian may be more technically tractable; however, they are areas in need of considerable research and technical development and must be solved at the pilot and demonstration plant level rather than at commercial scale.

3. RESOURCE REQUIREMENTS FOR COAL LIQUEFACTION

Major resource commitments for the various coal liquefaction technologies include coal, water, oxygen, ferrous and nonferrous metals, and specific catalysts. Since the coal liquefaction "module" or "unit" is generally considered to be 100,000 barrels per day, the resource requirements discussed here will be scaled to that size except where noted; however, the reader should be aware that these resource requirements are often scaled up from very small pilot plant data and thus could be inaccurate.

The most obvious resource requirement for coal liquefaction is coal itself. All of the technologies for coal liquefaction consume large quantities of coal. The Stanford Research Institute reports that the H-Coal process will require 18 million tons of subbituminous coal (8000-9000 BTU/lb.) per year, and a methanol synthesis gas plant would require 13 million tons of subbituminous coal or 18 million tons of lignite (6500 BTU/lb.).[22] The Radian Corporation reports that a modified SRC process will require 90,800 tons of 8806 BTU/lb. subbituminous coal per day (33.14 million tons/yr.) to produce 1 X 10^{12} BTU's per day of liquid fuel output.[23] ERDA and the U.S. Department of Interior state that a synthesis gas liquefaction plant will require 24.6 million tons of Powder River Basin, Wyoming, coal per year or 30.6 million tons per year of North Dakota lignite.[24] The same report indicates that a unit sized synthoil liquefaction plant will require 14.8 million tons of Wyoming subbituminous coal per year or 17.6 million tons per year of North Dakota lignite; a direct catalytic hydrogenation plant will use 15.4 million tons of Wyoming subbituminous coal per year or 18.4 million tons per year of North Dakota lignite; finally, a hydrocarbonization plant will use 16 million tons of Wyoming subbituminous coal per year or 19.2 million tons per year of North Dakota lignite. In summary, a 100,000 barrel per day coal liquefaction plant is likely to consume 15 to 30 million tons of coal per year depending on the specific process utilized.

The water requirements for coal liquefaction are also large since water is required both for cooling and for chemical reaction. Methanol production via the synthesis gas reaction requires about 3300 acre feet of water per year for the chemical reactions inherent in the process. Similarly, the H-Coal process requires about 3500 acre feet per year for necessary chemical reactions.[25] Methanol production requires an additional 12 - 24,000 acre feet of water per year for cooling purposes and the H-Coal process will consume 22,000 acre feet of water per year for cooling purposes.[26] The H-Coal annual cooling water consumption could be halved through the use of dry cooling.

Radian reports a makeup water consumption of 33.3 million gallons per day (37,000 acre ft./yr.) for a 1 X 10^{12} BTU/day synthetic liquid fuels plant using a modified SRC process.[27] The Synthetic Fuels Impact Statement indicates that a unit Fischer-Tropsch plant will require 58,300 acre feet of water per year for a location in the Powder River Basin in Wyoming or 56,600 acre feet per year for a location in the North Dakota lignite fields.[28] Water consumption in North Dakota is less because the lignite itself contains more water than does Wyoming subbituminous coal. The Synthetic Fuels Impact Statement also gives water requirements for a unit liquefaction plant other than Fischer-Tropsch. Such a plant would require 26,000 acre feet of water per year if it were located in the Powder River Basin in Wyoming or 24,600 acre feet per year in the North Dakota lignite fields. Thus, we see that a 100,000 barrel per day liquefaction plant will require upwards of 20,000 acre feet per year of water.

Some coal liquefaction processes also require oxygen. The synthesis gas process requires oxygen during the gasification step and the other processes will require oxygen if char or coal gasification is employed. Oxygen will be produced for the process by liquefying air and separating the various atmospheric constituents. The liquid air process is commercially available and there should not be great technical difficulties in its application to the liquefaction process; however, it is an energy intensive process. Depending on the process used, the production of synthesis gas requires between 6470 and 20,570 SCF of oxygen per ton of input coal processed.[29] For a modified SRC process producing 50 million SCF of synthetic gas and 40,000 barrels of fuel oil per day, a total 3055 tons of oxygen will be required to gasify coal to produce hydrogen for the process.[30]

The construction of synthetic liquid fuels plants will require large quantities of both ferrous and nonferrous metals and construction materials. The principal construction material requirement for the plants will probably be steel. The Stanford Research Institute has made a rough estimate that about 100,000 tons of steel would be required to build a 100,000 barrel per day liquefaction plant.[31] Another estimate places this steel requirement at 130,000 tons.[32] Copper is another critical material. Again, the Stanford Research Institute estimates that approximately 1500 tons of copper will be required for a coal liquefaction plant.[33] A 100,000 barrel per day Fischer-Tropsch plant has been estimated to require about 1200 tons of copper for construction.[34] Construction materials for a coal liquefaction plant will undoubtedly include several hundred thousand yards of concrete.

The catalyst requirements for coal liquefaction vary among the various processes. The SRC process, for instance, requires no catalyst. An H-Coal plant will require about 5500 tons of cobalt-molybdenum catalyst and 230 tons of nickel oxide catalyst per year.[35] For methanol synthesis, 875 tons of copper-chromium-zinc catalyst is consumed every 1 to 2 years.[36] Other catalysts used in methanol synthesis must be replaced every 2 to 5 years.

4. ENVIRONMENTAL IMPACTS OF COAL LIQUEFACTION

As can be seen by reviewing resource requirements, coal liquefaction is a heavy, potentially highly polluting industry. Environmental impacts from this sort of industry can be minimized but they cannot be entirely eliminated. The environmental impacts associated with coal liquefaction technology can be grouped into five major categories: Air pollution; water use, availability and pollution; solid waste; land use; and the occupational environment, or occupational heat and safety. Each of these categories will be discussed in detail in subsequent sections.

The environmental impacts related to the mining required to produce the coal used in the liquefaction process will not be discussed in this report. However, these impacts must not be ignored when the total environmental impact of coal liquefaction is considered. If the coal required to supply one coal liquefaction plant came from a single mine, that mine would today be the largest in the United States.

4.1 Air Pollution

Air pollution associated with coal liquefaction plants comes from essentially two sources, the combustion of fuels to provide electricity and process heat for liquefaction and from the process itself. There currently exist no Federal air pollution emission standards for coal liquefaction plants; however, because of the enormous quantities of coal being processed, anything less than "best available" air pollution control technology will emit unacceptably high levels of pollutants. In addition both Federal and State ambient air pollution standards would obviously apply to coal liquefaction plants.

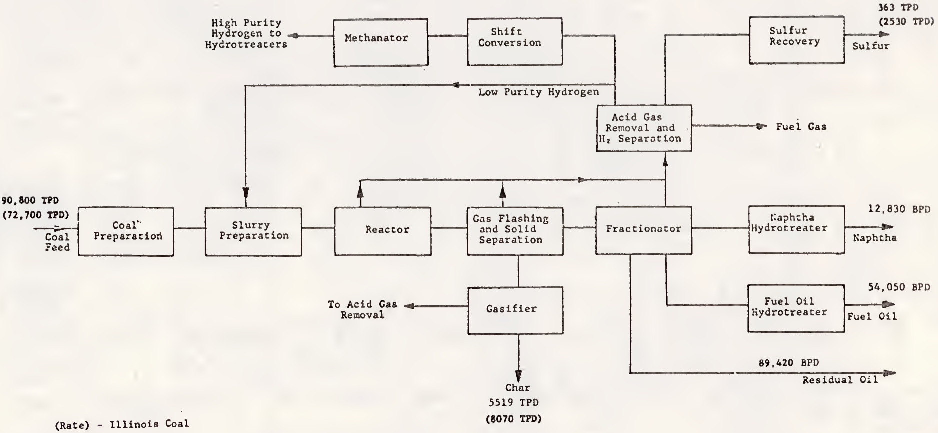
The Stanford Research Institute (SRI) reports that with "best available" technology a 100,000 barrel per day H-Coal liquefaction plant consuming Montana-Wyoming subbituminous coal would emit 4015 tons of sulfur dioxide, 2592 tons of particulate, 35,040 tons of nitrogen oxides and 584 tons of hydrocarbons per year.[37] SRI took this air pollution data and modeled the Powder River Basin coal region of Wyoming, a currently "clean" area with respect to air pollutants. SRI concluded that a single 100,000 barrel per day plant located in this region would not violate any existing Federal or State air quality standards. However, in order to meet the proposed Federal Class I "nondegredation" particulate standard, an additional 60 percent control beyond what is currently the best available technology would be required. It must be stressed that the above calculations were based on "best available" pollution control technology (99.5 percent particulate control, 90 - 95 percent SO_2 removal), and air quality standards may well be violated at lesser levels of pollution control. For comparison purposes, the Synthetic Fuels Impact Statement indicates that a unit Fischer-Tropsch liquefaction plant will emit 2900 tons of particulate, 12,720 tons of sulfur dioxide, 41,500 tons of nitrogen oxides, 920 tons of hydrocarbons, and 3080 tons of carbon monoxide per year. The same source states that a unit liquefaction plant of a process other than Fischer-Tropsch will discharge 1700 tons of particulate, 3000 tons of sulfur oxides, 9360 tons of nitrogen oxides, 180 tons of hydrocarbons, and 800 tons of carbon monoxide per year.

The Radian Corporation has also made a detailed study of potential air emissions from coal liquefaction plants. Figure 30 shows a schematic of Radian's coal liquefaction module (1 X 10^{12} BTU's of liquid fuel per day). Figure 31 gives a detailed breakdown of air emissions from various components of that module.

Coal also contains quantities of various toxic trace elements. The pathways of these trace elements through the coal liquefaction process and into the environment are presently not known; however, substantial quantities of some of these elements could be released into the environment through the air. In addition, Federal Standards for most trace elements do not currently exist. The transport, disposition, and effects of these trace contaminants is a research area that must not be ignored.

FIGURE 30

LIQUEFACTION MODULE



SOURCE: Radian Corporation, A Western Regional Energy Development Study, RC#100-064, Austin, TX, August, 1975.

FIGURE 31

AIR EMISSIONS AND STACK PARAMETERS - LIQUEFACTION MODULE - WESTERN COAL

BASIS: 10^{12} BTU OUTPUT/DAY

			Emissions lbs/Hr					Stack Parameters					
Source	Heat Input mm Btu/Hr	Fuel	Particulates	SO_2	Total Organics	CO	NO_x	Mass Flow lbs/Hr	ACFM	Velocity FPS	Height Ft.	Temperature °F	Diamete Ft.
1. Coal preparation	-		113.5										
2. Liquefaction Reactors (6 preheaters)	1105	1.07x10^6SCFH	19.3	28.8	3.22	18.2	257.5	975x10^3	338x10^3	60	200	450	11.72
TOTAL	6633	6.44x10^6SCFH	115.8	173.2	19.3	109.2	1545	5.85x10^6					
3. Distillation (2 stacks)	295	1.835x10^3 gal/Hr	42.1	106.6	7.34	7.34	73.4	254.7x10^3	97.5x10^3	60	200	450	5.87
TOTAL	590	3.67x10^3gal/Hr	84.2	213.1	14.7	14.7	146.8	509.3x10^3					
4. Fuel Oil HDS													
A. Reactor Heater	209	1.30x10^3gal/Hr	29.9	75.2	5.2	5.2	52.0	180.4x10^3	69.0x10^3	60	200	450	4.94
B. Reboiler Heater	155	963 gal/Hr	22.2	56.1	3.85	3.85	38.5	133.5x10^3	51.1x10^3	60	200	450	4.25
TOTAL	364	2.263x10^3 gal/Hr	52.1	131.3	9.05	9.05	90.5	313.9x10^3					

CONTINUED

SOURCE: Radian Corporation, A Western Regional Energy Development Study, RC#100-064, Austin, TX, August, 1975.

FIGURE 31 -- continued

			Emissions lbs/Hr					Stack Parameters					
Source	Heat Input mm Btu/Hr	Fuel	Particulates	SO_2	Total Organics	CO	NO_x	Mass Flow lbs/Hr	ACFM	Velocity FPS	Height Ft.	Temperature °F	Diameter Ft.
7. Shift Conversion													
A. Boiler I	281.3	1.75×10^3 gal/Hr	40.25	101.5	7	7	70	242.9×10^3	92.8×10^3	60	200	450	5.73
B. Boiler II	212.1	1.32×10^3 gal/Hr	30.38	76.6	5.28	5.28	52.8	183.3×10^3	70.1×10^3	60	200	450	3.77
C. Hot Shift Htr	120.8	0.75×10^3 gal/Hr	17.25	43.8	3	3	30	104.0×10^3	39.8×10^3	60	200	450	3.75
TOTAL	614.2	3.82×10^3 gal/Hr	87.88	221.9	15.28	15.28	152.8	530.2×10^3					
8. Sulfur Recovery TGTU (2 stacks)				212.7				1.08×10^6	403.3×10^3	60	200	450	11.95
TOTAL				425.3				2.16×10^6	806.6×10^3				
9. Power Generation (6 units)	1118.7	1.09×10^6 SCFH	16.3	29.3	1.09	18.46	651.7	988.3×10^3	392.9×10^3	60	200	450	11.79
TOTAL	6712	6.52×10^6 SCFH	97.77	175.4	6.52	110.75	3910	5.93×10^6	2.36×10^6				
10. Steam Generation (6 units)	727.1	0.706×10^6 SCFH	10.6	19.0	0.71	12	423.8	641.7×10^3	255.3×10^3	60	200	450	9.50
TOTAL	4362.5	4.24×10^6 SCFH	63.5	114.0	4.25	72	2542.5	3850×10^3	1532×10^3				

FIGURE 31 -- continued

Source	Heat Input mm Btu/Hr	Fuel	Emissions lbs/Hr						Stack Parameters					
			Particulates	SO_2	Total Organics	CO	NO_x	NH^3	Mass Flow lbs/Hr	ACFM	Velocity FPS	Height Ft.	Temperature °F	Diamete Ft.
11. Refining Misc.					2525							5		
12. Storage					10.4			25.5				50		
TOTAL			633.0	1493	2607.6	340.0	8507.5	25.5						

4.2 Water Use, Availability, and Pollution

The problems of water use and availability in the semi-arid Western lands where coal liquefaction plants are likely to be located have been mentioned previously. The consumption of 15 - 30,000 acre feet of water per year per plant is of real significance in this region where several existing rivers may be already overappropriated. Because of the serious problems of water use and availability, companies planning coal liquefaction projects are likely to focus on limiting consumptive use of water wherever possible through recycling or other means. In fact, the Radian Corporation coal liquefaction module was designed to have "zero liquid discharge" from the system.[39] Radian indicates that the means of achieving this zero discharge goal are still being researched.

Zero discharge from the plant site will have an obvious effect on the environmental impact of liquid effluents from the liquefaction process. In most zero discharge schemes waste process water is treated and used to replace water lost from evaporative cooling towers. If the "zero discharge" concept is not utilized considerable liquid effluent results. SRI states that a 100,000 barrel per day coal liquefaction plant produces about 5,000,000 gallons of waste water per day.[40] This water must be treated to remove ammonia and hydrogen sulfide and then undergo biological treatment. The resultant biologically treated water has the following pollutant concentrations:

FIGURE 32

COAL LIQUEFACTION PLANT BIOLOGICAL TREATING POND WATER EFFLUENT

Constituent	Concentration (wt ppm)
Sulfide	< 0.005
Ammonia	0.11
Oil	0.68
Biological oxygen demand (BOD)	10.5
Suspended solids	12.9
Phenol	0.38
Chemical oxygen demand (COD)	45
Phosphate	0.11
Chromate	7.1
Zinc	3.5

Certain trace metal and other contaminents may hinder the biological treatment process by killing the bacteria used in the process.

4.3 Solid Waste

The primary solid waste from the coal liquefaction process is ash. This ash represents the inorganic constituents in the original coal which are incombustible. Some liquefaction processes also produce a char of low carbon content which is unsalable and must be disposed of. This ash and char from a 100,000 barrel per day plant may amount to 3000-4000 tons per day. It is often suggested that this char and ash can be disposed of in strip mine pits. Trace constituents may leach from the ash and the char may be biologically active so their disposal cannot be summarily dismissed.

4.4 Land Use

A 100,000 barrel per day liquefaction plant consuming more than 15 million tons of coal per year will require considerable land for physical facilities. It is expected that a coal liquefaction plant will require about 1000 acres for its physical plant. The associated coal mine will also require considerable land as at least 300 to 400 acres will be strip mined each year (50,000 tons per acre).

4.5 Occupational Health and Safety

The work place environment of a coal liquefaction facility must also be considered. The Radian Corporation presents some brief data on occupational health related to their 1 X 10^{12} BTU/day coal liquefaction module.[41] They indicate that 0.511 deaths, 9.9 injuries and 2372 days lost per year will be associated with the facility.

The carcinogenic nature of synthetic fuels is of particular concern since typical coal liquefaction products include polycyclic aromatic compounds. It has been reported that a high incidence of skin cancer in plant workers was associated with the operation of an early coal liquefaction pilot plant.[42] Workers in coal liquefaction pilot and demonstration plants should be carefully monitored and precautions should be taken to avoid contact with carcinogenic materials. The Stanford Research Institute concludes that a great deal needs to be learned about the health effects of synthetic fuel manufacture and use.[43]

5. ECONOMIC FACTORS RELATED TO COAL LIQUEFACTION

A detailed social and economic analysis of coal liquefaction is beyond the scope of this report. Here we will focus on three important economic aspects of coal liquefaction: The initial capital investment necessary to build a synthetic liquid fuels plant, the construction labor force required, and the total operating work force.

5.1 Coal Liquefaction Capital Investment

The capital costs of coal liquefaction are very uncertain at this time due to uncertainties in technology, environmental considerations, and inflation. Capital cost information less than one year old is now outdated and the capital cost data reported here must therefore be viewed with suspicion.

The Stanford Research Institute reports that the capital investment for a 100,000 barrel per day liquefaction plant would be "in the neighborhood of" \$1 billion (1973 dollars).[44] Exxon research indicates that a 100,000 barrel per day synthetic crude plant using Southwestern United States coal would require a capital investment of \$1,013.6 million (1973 dollars).[45] An H-Coal plant is estimated to have a capital cost of \$687.7 million based on 1967 data scaled to 1974.[46] A modified SRC plant producing 175 million SCF per day of synthetic natural gas and 143,000 barrels of liquid hydrocarbons is expected to have a fixed capital investment of \$1,250 million exclusive of financing charges.[47] Finally, a COED plant capable of producing 200 million SCF of pipeline quality synthetic gas and 25,000 barrels of synthetic crude is estimated to have a capital cost of \$522 million.[48]

5.2 Labor Requirements for the Construction of a Coal Liquefaction Plant

There exist a few estimates of the labor required to build a coal liquefaction plant. The Stanford Research Institute estimates that approximately 7500 man years are required to build a 100,000 barrel per day methanol plant. Construction will require 3 years and the work force will peak at about 3500.[49] They also estimate that between 7000 and 8000 man years will be required to build a coal liquefaction plant. Construction will require 3 to 4 years and the labor force will peak at 2000 to 3000. Construction of a 25,000 barrel per day COED plant with gasification capabilities will require 4 years and the construction work force will peak at 3500.[50] The Synthetic Fuels Impact Statement also presents detailed construction work force estimates which are shown in Figures 33 and 34. It should be noted that these data refer to only a 50,000 barrel per day plant and should be scaled for a 100,000 barrel per day plant.

5.3 Operating Manpower Requirements for Coal Liquefaction

Coal liquefaction plants will require a relatively large operating work force. SRI states that 900 people will be required to operate a 100,000 barrel per day methanol plant and that 1400 people will be employed by an operating coal liquefaction plant.[51] A 24,000 barrel per day COED plant with char gasification will require an operational work force of 1619.[52] Estimates of operational manpower requirements for two different 50,000 barrel per day liquefaction plants are shown in Figures 35 and 36.

FIGURE 33

MANPOWER REQUIREMENT FOR CONSTRUCTION OF A 50,000 BARREL/DAY FISCHER-TROPSCH PLANT

Occupational Groups/ SIC Code	Manpower Requirement					
	Year 1	Year 2	Year 3	Year 4	Year 5	Total
Carpenter/415	18	42	24	30	6	120
Cement/Cons. Fin./421	3	7	10	7	3	30
Iron Worker/550	21	31	26	21	5	104
Laborer/751	28	35	40	34	14	151
Millwright/502	1	4	2	3	1	11
Exc. Equip. Op./412	56	28	17	6	6	113
Pipefitter/522	19	74	130	93	56	372
Electrician/430	18	41	39	53	27	178
Asb. Worker	4	17	17	25	13	76
Painter/510	0	2	15	19	2	38
Sheet Metal Worker/535	8	22	37	60	22	149
Masons/410	1	4	3	0	0	8
Teamster/715	7	12	7	4	5	35
Drafting/152	30	8	2	0	0	40
Surveying/161	5	0	0	0	0	5
Boilermaker/404	22	28	24	27	11	112
Welder/228	10	24	22	18	4	78
Engineering/010	7	27	22	83	4	143
011	7	47	38	145	6	243
012	6	27	22	83	4	142
014	3	15	13	47	2	90
021	3	0	0	0	0	3
002	6	0	0	0	0	6
Total All Occupations	283	495	510	758	191	2237

SOURCE: U.S. Department of Interior, and U.S. Energy Research & Development Administration. Synthetic Fuels Commercialization Program Draft Environmental Statement ERDA-1547. Washington, D.C., December, 1975.

FIGURE 34

MANPOWER REQUIREMENTS FOR CONSTRUCTION OF A 50,000 BARREL/DAY LIQUID FUEL PLANT, OTHER THAN FISCHER-TROPSCH

Occupational Groups/ SIC Code	Manpower Requirement					
	Year 1	Year 2	Year 3	Year 4	Year 5	Total
Carpenter/415	18	42	23	29	6	118
Cement/Cons. Fin./421	3	7	10	7	3	30
Iron Workers/550	22	32	30	21	5	110
Laborer/751	27	35	39	33	14	148
Millwright/502	1	4	2	3	1	11
Exc. Equip. Op./412	54	27	17	6	6	110
Pipefitter/522	18	73	127	91	54	363
Electrician/430	18	40	38	92	26	214
Asb. Worker	4	16	16	24	12	72
Painter/510	0	2	15	18	2	37
Sheet Metal Worker/535	7	22	36	58	22	145
Masons/410	1	4	3	0	0	8
Teamster/715	7	12	7	4	5	35
Drafting/152	29	8	2	0	0	39
Surveying/161	5	0	0	0	0	5
Boilermaker/404	22	27	23	26	11	109
Welder/228	10	23	21	18	4	76
Engineering/010	5	30	15	10	5	65
011	10	40	35	10	5	100
012	5	25	25	10	5	70
014	5	30	25	10	0	70
021	0	10	10	5	0	25
002	15	60	50	15	0	140
Total All Occupations	286	569	569	490	186	2100

SOURCE: U.S. Department of Interior and U.S. Energy Research & Development Administration. Synthetic Fuels Commercialization Program Draft Environmental Statement ERDA-1547. Washington, D.C., December, 1975.

FIGURE 35

OPERATIONAL MANPOWER REQUIREMENTS FOR A 50,000 BARREL/DAY FISCHER-TROPSCH PLANT

Labor Category	Number of Workers
Operating	
Operator	43
Helper	33
Controlman	12
Pumper	13
Utility Man	12
Fireman, Stat.	5
Foreman	14
	132
Maintenance	
Instrument Technician	19
Mechanic, Machine	19
Equipment Operator	17
Welder	21
Bricklayer	8
Bricklayer Helper	8
Electrician	19
Electrician Helper	19
Carpenter	9
Painter	8
Pipefitter	21
Pipefitter Helper	21
Mechanic	19
Mechanic Helper	19
Master Machinist	14
General Maintenance	50
Foreman	38
Sub Total	329

Labor Category	Number of Workers
Service/Administration	
Management	11
Sales	9
Personnel Department	9
Accounting	5
Safety/Fireman	7
Medical	7
Maintenace Room	10
Security	11
Secretarial	7
Warehouseman	7
Office Service	7
Engineering and Technical	
Chemical	8
Electrical	7
Statistician	6
Computer Programmer	6
Chemist	8
Mechanical	7
Sub Total	132
Total Number of Workers	593

SOURCE: U.S. Department of Interior, and U.S. Energy Research & Development Administration. Synthetic Fuels Commercialization Program Draft Environmental Statement ERDA-1547. Washington, D.C., December, 1975.

FIGURE 36

OPERATIONAL MANPOWER REQUIREMENT FOR A 50,000 BARREL/DAY LIQUEFACTION PLANT OTHER THAN FISCHER-TROPSCH

Labor Category	Number of Workers
Operating	
Operator	48
Helper	38
Controlman	11
Pumper	16
Utility Man	3
Fireman, Stat.	3
Foreman	14
Sub Total	133
Maintenance	
Instrument Technician	19
Mechanic, Machine	15
Equipment Operator	18
Welder	22
Bricklayer	5
Bricklayer Helper	5
Electrician	20
Electrician Helper	20
Carpenter	3
Painter	2
Pipefitter	23
Pipefitter Helper	23
Mechanic	16
Mechanic Helper	16
Master Machinist	13
General Maintenance	65
Foreman	35
Sub Total	320
Service/Administration	
Management	10
Sales	5
Personnel Department	5
Accounting	5
Safety/Fireman	4
Medical	5
Maintenance Room	8
Security	10
Secretarial	7
Warehouseman	8
Office Service	5
Engineering and Technical	
Chemical	8
Electrical	6
Statistician	1
Computer Programmer	2
Chemist	6
Mechanical	6
Sub Total	101
Total Number of Workers	554

SOURCE: U.S. Department of Interior, and U.S. Energy Research & Development Administration. Synthetic Fuels Commercialization Program Draft Environmental Statement ERDA-1547. Washington, D.C., December, 1975.

6. COST OF SYNTHETIC LIQUID FUELS FROM COAL

Cost estimates for synthetic liquid fuels from coal abound in the literature. With each passing year those estimates grow higher. Only part of this increase in costs is due to inflation. A considerable part of the increase is due to design modifications which occurred when actual commercial designs were developed. These cost estimates are very sensitive both to capital costs and the rate of return on investment. Also, according to Hammond and Baron, the costs of synthetic fuels are also extremely dependent on the "stream factor" (the amount of actual annual output/designed annual output assuming continuous operation). The best oil refineries have a stream factor of about 0.91. The economic analyses of synthetic liquid fuels production generally assume a similar stream factor. If the actual stream factor were .5 the costs of synthetic fuels production would increase by 100 percent.

The Stanford Research Institute estimates that synthetic liquid fuels from coal will have a market price range of $12 to $17 per oil equivalent barrel.[53] The Stanford Research Institute interfuels substitution energy model assumes a cost of $3.45 per million BTU of syncrude from coal, and $3.05 per million BTU's for fuel oil from coal.[54] For comparison, the 1975 average cost of imported liquid fuels was $1.90 per million BTU's.

Cochran gives cost estimates for the four major categories of coal liquefaction processes.[55] The Coalcon pyrolysis would produce synthetic natural gas to sell at $2.40 per million SCF, fuel oil at $15 per barrel and gasoline at $ .33 per gallon (tax excluded). The Direct Hydrogenation process would produce synthetic liquids at $14 to $18 per barrel while a solvent hydrogenation process would produce synthetic natural gas at $2.30 per million SCF and synthetic crude oil at $15 per barrel. Finally, the Fischer-Tropsch process would produce gas at $2.25 per million SCF and gasoline at $13.05 per barrel ($ .31 per gallon). All of Cochran's data are in 1975 dollars.

Most 1974 and previous synthetic liquid fuel data give costs in the range of $10 per barrel or below. For comparison, a single 1976 source states that synthetic liquid fuels will cost as much as $25 per barrel.[56]

The Process Evaluation Group at the U. S. Bureau of Mines, Morgantown, West Virginia have recently conducted a number of cost estimates for the production of synthetic liquid fuels. This group estimates that the liquid hydrocarbon product from the Synthoil process using Wyodak coal would cost from $15.69-$24.84, depending on input coal costs and rate of discounted cash flow. Similarly an H-Coal plant using Wyodak coal would produce boiler fuel at $18.02-$28.19. Finally they estimated that the SRC process would produce liquid fuel from Wyodak coal at $16.87-$26.76.

7. BYPRODUCTS FROM THE COAL LIQUEFACTION PROCESS

Depending on the specific process under consideration, coal liquefaction produces a wide variety of byproducts. Usable byproducts can be sold on the open market to create additional revenue and thus help to reduce the production costs of synthetic liquid fuels. Since coal liquefaction processes are so catipal intensive, many of the processes will depend on the sale of byproducts to make them competitive. Unfortunately byproducts from liquefaction plants could ultimately saturate their markets, hence reducing their value. Typical byproducts include hydrocarbon gases, light aromatics, oils and tars, ammonia, hydrogen sulfide, sulfur dioxide, phenols and cresols, and char and ash.

Coal liquefaction processes also can be designed to minimize the production of byproducts. For example the H-Coal process uses its synthetic gas and heavy bottoms for plant fuel and hydrogen production. The only potentially salable products from the process are approximately 300-400 tons per day of ammonia and 200-1300 tons per day of sulfur.

The conversion of coal to methanol also produces a wide variety of byproducts. These products are produced both in the production of synthesis gas and in the purification of the catalytically synthesized methanol. According to the Stanford Research Institute the following quantities of byproducts would be produced from the production of 100,000 barrels per day of methanol from western coal:

Tan, Oil, and Naphtha	15,200 Barrels/Day
Phenols	840 Barrels/Day
Higher Alcohols	405 Barrels/Day
Ammonia	450 Tons/Day
Sulfur	170 Tons/Day

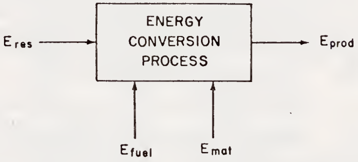
The higher alcohols are separated from methanol by distillation.

8. NET ENERGY ANALYSIS OF COAL LIQUEFACTION

Net energy analysis has been developed as a tool to understand energy efficiency. The thermal efficiency of the various coal liquefaction processes has been previously discussed. Here we will analyze the net energy of coal liquefaction. Net energy is a measure of the energy return per unit of energy invested in the energy-producing sectors of the economy.[57] The following flow diagram shows how net energy is defined for an energy conversion process:

FIGURE 37

FLOW DIAGRAM FOR DEFINITION OF NET ENERGY RATIO



$$\text{NET ENERGY RATIO} = \frac{E_{prod}}{(E_{res} - E_{prod}) + E_{fuel} + E_{mat}}$$

SOURCE: Stanford Research Institute. Impacts of Synthetic Liquid Fuel Development--Automotive Market. Draft Final Report. Menlo Park, CA, January, 1976.

E_{res} is the energy content (heating value) of the input energy resource and E_{prod} is the energy content of the product produced by the energy conversion process. E_{prod} is always less than E_{res} (1st and 2nd laws of Thermodynamics). E_{fuel} represents any externally supplied fuel inputs into the process and E_{mat} is the energy required to build and maintain the energy conversion facility and fabricate the materials used in its construction. Thus, the Net Energy Ratio is simply the energy contained in the final product divided by the energy lost in the conversion process plus the energy consumed in fuel or materials input into the process. The Net Energy Ratio can have any value from zero to infinity. Net Energy Ratios less than unity indicate that more energy was consumed in the energy conversion process than was produced as a final product. Thus high Net Energy Ratios are desirable.

The Stanford Research Institute has calculated Net Energy Ratios for coal liquefaction processes.[58] For a 100,000 barrel per day H-Coal liquefaction plant using Powder River Basin coal, the Net Energy Ratio is 1.5. If the entire resources to fuels system is considered (pipelines, refinery, etc.) the Net Energy Ratio for coal liquefaction is 1.1. For a 100,000 barrel per day methanol plant using Lurgi gasifiers and Southwestern U.S. coal, the Net Energy Ratio is 0.64. Since methanol does not have to be refined, very little additional energy is consumed in the resources to fuels system. The Net Energy Ratio for the Methanol Resources to fuels system is 0.62. For comparison, the Net Energy Ratio for the surface mining of coal is 54, the TOSCO II oil shale process has a Net Energy Ratio of 2.3, and the production of electricity has a Net Energy Ratio of 0.36.

9. TECHNICAL SUITABILITY OF COAL LIQUEFACTION TO MONTANA

The major criteria for the technical (not social, economic, or environmental) suitability of the coal liquefaction process to the State of Montana are the availability of large quantities of coal, the ability to utilize that particular coal in the liquefaction process, and the availability of large quantities of water.

The availability of large quantities of coal in Montana is well known. Matson lists 20 individual coal fields in Southeastern Montana with reserves greater than 500 million tons, the minimum quantity required for a single 100,000 barrel per day plant processing 20 million tons of coal per year and operating for 25 years.[59] Large reserves of lignite are also located north of the Yellowstone River in Montana and are not described in Matson's report. Montana's coal is generally non-agglomerating and is thus suitable for coal liquefaction. Agglomerating coals will require pretreatment (and probable efficiency losses) before they can be liquefied. Montana coal is also generally more reactive than eastern bituminous coals. The gross chemical composition of Montana coal appears suitable for liquefaction; in fact the lower sulfur content of Montana coals will permit the use of less hydrogen in liquefaction. Water is also available in Montana, although not necessarily coincident with the coal fields. In addition, the legal "water rights", appropriation, use, availability, and ownership framework for water in the Eastern Montana coal regions must be clarified before large quantities of water are appropriated for coal liquefaction.

Two other criteria are also of interest for this report. These criteria are the availability of an existing pipeline system to transport synthetic crude to refineries and the ability of existing refineries in Montana to process this crude.

Montana's crude oil pipelines are shown in Figure 38. The major pipelines within the State are the Butte pipeline system along the eastern border of Montana, and the Continental Oil-Glacier pipeline which travels through central Montana to Billings and then south into Wyoming. The Butte pipeline passes relatively close to some large Eastern Montana coal fields; however, it does not connect with any Montana refining centers. New pipelines will likely have to be constructed if synthetic crude is to be processed in Montana.

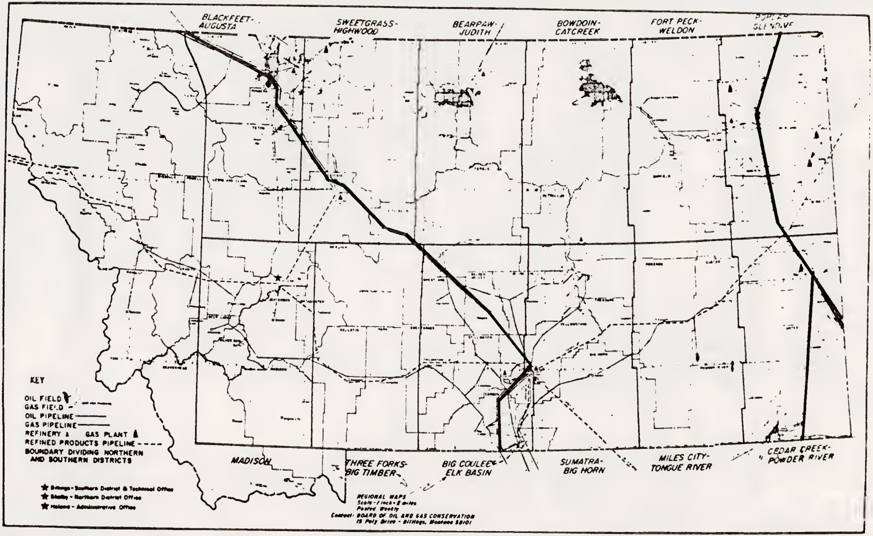
Montana refineries are capable of refining over 157,000 barrels of crude per day and over the last 2 years have operated at about 84 percent capacity. A total of 88 percent of this refinery capacity is located at Billings, Montana. Montana refineries currently receive over 19 million barrels of crude oil annually from Canada, or 40 percent of all Montana refinery feedstock. This Canadian supply may soon be curtailed and alternative sources of crude oil supply for Montana refineries are being explored. It is thus important to determine whether synthetic crude oil from coal can be utilized in Montana's existing refineries.

The characteristics of coal derived synthetic crude oil have been determined primarily from pilot plant operation and such data are very limited. Much more data must be assembled before the suitability of synthetic crude to Montana's existing refineries can be accurately determined. From the limited existing data, it is known that coal syncrude will be highly aromatic. The gasoline fraction from coal syncrude may have 50 to 60 percent aromaticity.[60] The Cetane Index of the diesel fuel produced from coal syncrude will also probably be low (35-38) compared to the 40-45 required for automotive diesel fuel. Properties of syncrude derived from the H-Coal process are shown in Figure 39.

A preliminary survey of the Billings refineries indicated that coal syncrude probably could be blended into the feedstock of the existing refineries. But it

FIGURE 38

MONTANA OIL PIPELINES



SOURCE: Montana Energy and MHD Research and Development Institute. Siting Energy Facilities at Glasgow Air Force Base. Washington, D.C., FEA 16-75/420, November, 1975.

FIGURE 39

PROPERTIES OF SYNCRUDE FROM THE H-COAL PROCESS

Boiling Range:	Initial/375°F	375/650°F	650/975°F	Total
Gravity, °API	53.0	23.2	3.5	32.4
Vol.% on Total	40.0	54.2	5.8	100.0
Analysis (Wt.%)				
Carbon	84.5	88.8	89.4	87.3
Hydrogen	13.6	11.0	10.2	11.9
Oxygen	1.7	--	--	0.6
Nitrogen	0.1	0.1	0.1	0.1
Sulfur	0.1	0.1	0.3	0.1

SOURCE: Kant, F. H., et al. Feasibility Study of Alternative Fuels for Automotive Transportation. Exxon Research and Engineering Co., Linden, N.J. EPA-460/3-74-009-a, June, 1974.

appears questionable whether adequate quantities could be blended to eliminate the Canadian crude imports without additional capital investment. More analysis will be required to definitely resolve whether coal syncrude can replace the existing Canadian crude oil inputs.

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